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A Role for Optimization and Simulation Modeling

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This report presents a structured approach for applying prescriptive (optimization) and descriptive (simulation) models to help identify alternative operational strategies. As part of this process, a method to quantify objectives for different water uses without a complete economic analysis is presented. Quantifying each water use objective requires adoption of a numerical scale to provide an indicator for measuring the effectiveness of alternative operational strategies. This indicator of effectiveness is necessary to analytically compare different operational strategies. The technique shown allows representation of water values through relative unit costs according to value categories set by the interest groups.

To demonstrate the modeling approach and test the methodology for quantifying objectives, a single reservoir system is analyzed according to the procedures advocated. The advantages and difficulties of applying this optimization-simulation approach to help resolve conflict are discussed.

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Preface

This report presents some thoughts about using optimization and simulation models to help address conflicts over reservoir system operation. The report explores a systematic method to formulate quantitative representations of different water use interests without using an explicit economic approach. The proposed method is tested by applying it to an actual conflict situation surrounding operation of Alamo reservoir in Arizona.

The work outlined in this report was done in 1994 to help develop methods to use the Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) for cases where explicit economic data are not available. This report provides background for two more-detailed studies. Model results from this case study on Alamo reservoir were used as a starting point for a more detailed modeling study presented in *Technical Considerations for Alamo Lake Operation* (USACE 1998a). The method to formulate non-economic value functions for water uses also was used to study potential water infrastructure changes in Central and South Florida (USACE 1998b).

Kenneth W. Kirby conducted this study. Michael Burnham, Chief, Planning Analysis Division, provided study direction and management. Darryl W. Davis was Director of HEC during the conduct of the study. The Los Angeles District provided data and general guidance for this study.

Executive Summary

Conflict over reservoir operation increases the need for analytical tools to help reevaluate reservoir system operation. This report presents an analytical approach combining optimization and simulation models to develop a range of feasible reservoir operation alternatives to help advocacy groups in conflict more quickly find a suitable compromise. One difficulty in applying optimization models is developing quantitative value functions for water management objectives that cannot be readily represented in economic terms. This report presents a systematic method to construct quantitative value functions without formal economic analysis.

The proposed modeling approach is demonstrated by reevaluating the operation of Alamo Lake, Arizona in light of current conflicts. The results of this study demonstrate that this approach can be useful to help resolve conflict over reservoir operations. The non-economic method presented to create numerical value functions can allow analysts to use optimization models even when a complete economic analysis is not feasible.

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Introduction

Increasing demands for water, especially for environmental purposes, present difficult problems for reservoir managers. The political, social, and economic climate has changed significantly since many reservoirs were constructed in the 1950's and 60's. Most reservoirs are now subject to legislation (such as the Endangered Species Act) passed after their original authorizing legislation. The specific problems vary from region to region, but many reservoir managers face demands to reevaluate operational strategy to more closely meet current demands. Often, these demands are from disparate interests in conflict over how the reservoirs should be operated. Addressing conflicts over water includes many facets such as establishing communication, quantifying objectives and evaluation criteria, and identifying and evaluating potential changes (USACE 1994b). Frequently, some type of reservoir system model is necessary (but not sufficient) to find satisfactory solutions. This report addresses the importance of quantifying objectives and analyzing alternatives to help find a workable compromise between those in conflict. These tasks are only a subset of conflict resolution activities, and usually much work is needed to reach the point in the process where the tools presented here could be useful.

This report presents a structured approach for applying prescriptive (optimization) and descriptive (simulation) models to help identify alternative operational strategies. As part of this process, a method to quantify objectives for different water uses without a complete economic analysis is presented. Quantifying each water use objective requires adoption of a numerical scale to provide an indicator for measuring the effectiveness of alternative operational strategies. This indicator of effectiveness is necessary to analytically compare different operational strategies. The technique shown allows representation of water values through relative unit costs according to value categories set by the interest groups.

To demonstrate the modeling approach and test the methodology for quantifying objectives, a single reservoir system is analyzed according to the procedures advocated. The advantages and difficulties of applying this optimization - simulation approach to help resolve conflict are discussed.

1.1 Modeling Reservoirs to Resolve Conflict

Recently, computer modeling has been advocated for a central role in resolving water resource conflicts (USACE 1991a; 1994b). A recent final report from the National Drought Study states: "The most visible innovation of the National Drought Study is the use of stakeholders' collaboratively built 'shared vision (computer) models' of their management environments." (USACE 1994b).

Some tasks necessary to resolve conflict regarding water include: identifying stakeholders and decision makers, defining regional objectives and constraints of stakeholders and decision makers, identifying areas of conflict, evaluating current conditions, generating alternatives, and selecting alternatives. Computers and computer modeling now have an important role in providing information for the tasks of conflict resolution.

1.2 Types of Models

Two categories of computer models available for use in conflict resolution are *descriptive* or *prescriptive*. *Descriptive* models demonstrate what will happen if specified decisions are made. *Prescriptive* models determine what decisions should be made to achieve specified objectives (USACE 1991c). Models are also commonly classified as *optimization* or *simulation* (Yeh 1985). Simulation models are descriptive, although some simulation models include optimization algorithms to perform key calculations. Most optimization models are based on some type of mathematical programming algorithm and are prescriptive. The mathematical programming techniques used for optimization models include linear programming (LP), dynamic programming (DP), and non-linear programming (NLP). The final distinction between types of models depends on how stream flow uncertainties are considered (Yeh 1985). The two general categories regarding uncertainty are *deterministic* and *stochastic*. Deterministic model formulations do not consider uncertainty explicitly, whereas stochastic models try to account for uncertainty directly in the model formulation.

The proposed modeling strategy presented in this report uses both an optimization model and a simulation model. The optimization model is used to generate and screen promising alternatives for mitigating conflict, and the simulation model is used to test and refine promising alternatives from the optimization model results. This screening and refining technique is similar to that proposed by Jacoby and Loucks (1972).

1.3 Modeling Uncertainty

Inflow data used to model a reservoir system inherently contain hydrologic uncertainty. Optimization techniques have been developed that address the problem of uncertainty in a variety of ways using both deterministic and stochastic model formulations. A simple approach for considering uncertainty is sensitivity analysis. In this popular approach the analyst strategically varies the more uncertain parameters or variables of a deterministic model and then examines the results. Sensitivity analysis provides a way of identifying those parameters or variables to which system performance is particularly sensitive and offers some idea of the types and magnitudes of deviations possible (Loucks, *et al.* 1981).

Another approach uses a deterministic model and relies on a long sequence of historical or synthetic hydrologic inflows to represent uncertainty. This approach is sometimes called "implicitly stochastic optimization" (Whitlatch and Bhaskar, 1978; Klemes, 1979; Karamouz, et al., 1992). The patterns evident in the deterministic optimization results based on very long stream flow records should represent optimal rules for operations even under uncertainty.

Theoretically, if a long enough hydrologic record is used to perform the deterministic reservoir optimization, a set of rules could be compiled to establish the mean optimal release from each reservoir given the current month, current storages, and current inflows throughout the system. Young (1966) did this for a single idealized reservoir using 5,000 periods of synthetic inflows with one season. According to Lund (USACE 1992), it is unlikely that this ideal release table could be developed for most real reservoir systems that have significant monthly variation, multiple reservoirs, and less than 100 years of hydrologic record. Nonetheless, implicitly stochastic optimization approaches applied with less than ideal conditions producing more approximate rules are common in the reservoir optimization literature (Young 1966; Whitlach and Bhaskar 1978; Bhaskar and Whitlatch 1980; Trott 1979; Karamouz and Houck 1982; Karamouz *et al.* 1992; USACE 1992; USACE 1994a). Various stochastic formulations have been devised to consider uncertainty explicitly, but computational demands tend to be very extensive, and input requirements such as stochastic stream flow models can be elusive (Yeh 1985; Young 1966; USACE 1992).

1.4 Cautions

Although attempts are made to account for stream flow uncertainty, other data used for modeling reservoir operation such as population estimates, water usage rates, and expected damage due to flooding also contain uncertainty. These uncertainties can have a major impact on the performance of water resource systems analysis in a physical, ecological, and economic sense. Although the analyst can model uncertainty and explain its consequences using various indicators, one cannot eliminate uncertainty or even reduce its impact to the point of insignificance. Major sources of uncertainty will always be present (Loucks, *et al.* 1981).

This uncertainty, coupled with the possibility of unclear (and often continuously evolving) preferences by the public or specific interest groups, can make it very difficult to choose one alternative over another. It is likely, due to the pluralistic nature of our society, that the public (as represented by the decision makers) will be indifferent between several alternatives. At the same time, particular groups of individuals probably will express intense preferences regarding specific alternatives. One alternative will rarely qualify as a *best-compromise* solution (where all interests get what they desire). Rather, it is more reasonable to seek an alternative where all interest groups can be sufficiently *satisfied* to end the conflict.

Chapter 2

Proposed Modeling Strategy

A reservoir system modeling effort is more likely to be successful if conducted systematically. This report presents a series of seven steps to guide an analyst through a procedure intended to produce a range of promising operational alternatives to be considered in the conflict resolution process (See Figure 2.1). This procedure is primarily an analytical tool to aid in *part* of the conflict resolution process. Although this process does not cover all aspects of conflict resolution, the structured analytical strategy can help focus activities or provide a common point of reference for the stakeholders in conflict. This focus can help start the resolution process and help keep it moving.

Overall, the strategy applies an optimization model to screen alternatives, and then uses a simulation model to test and refine the more promising alternatives. It is important to understand the intent of this approach and its impacts on the notion of optimality. Although the procedure uses an optimization model, there is no claim of producing a "global optimum" solution for meeting conflicting demands on multiple purpose reservoirs. In fact, the complex multi-objective nature of this problem coupled with the simplifications required to solve these problems analytically, render the possibility of discovering an analytical "global optimum" impossible (Cohon 1978; Jacoby & Loucks 1972). Nonetheless, the analytical effort can still be worthwhile for conflict resolution efforts. Used together, optimization and simulation models can efficiently produce a range of viable alternatives to help those in conflict reach an acceptable compromise.

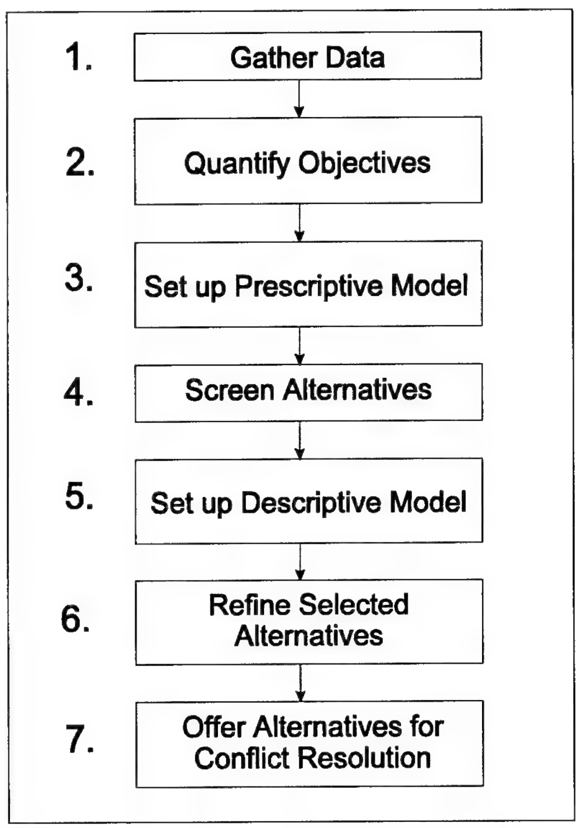

Figure 2.1 Proposed Modeling Strategy

2.1 Gather Data

To analyze reservoir operation with computer models, representative input data describing the reservoir system must be gathered and formatted for the chosen model. The three areas of information usually required include inflow hydrology, water management objectives, and system constraints. If the water management objectives explicitly involve water quality parameters for the system being studied, more input data will be required. Some examples include temperature, salinity, dissolved oxygen level, and specific ion concentration. This report focuses specifically on the water quantity problem and not the water quality problem. Studies of water quality problems require specific model formulations that often are not included in general reservoir models.

Hydrology

Computer modeling of reservoir operation requires information that describes stream flows in the system. Historical records of either stream flow or precipitation for the reservoir system area are required. Ideally, a long record of measured unregulated stream flow data at each reservoir and other points of interest would be available. This rarely happens in practice, but since this analysis involves existing reservoirs, some record of stream flow data should be available. For systems with 25 years or less of historic stream flow data or where over-year storage is important, the historic stream flow sequence may not be adequate. Also, the exclusive use of historic stream flows yields only one sequence of the system's operation. Various techniques have been developed to generate long sequences of stream flows for testing alternatives over many different potential hydrologic sequences. These generated stream flows are called *synthetic* or *operational* to distinguish them from historic observations (Salas 1993).

Two basic techniques exist to generate stream flow data. If the historical stream flow data can be described by a stationary process (meaning the parameters do not change with time), a statistical stream flow model can be fit to the historic flows. The statistical model can then generate synthetic sequences that reproduce specific statistical characteristics of the historic flows. In the absence of stationarily of stream flows or a representative historic record, the analyst can assume that precipitation is a stationary stochastic process and use that data along with a rainfall-runoff model of the river basin to generate potential stream flows. Loucks, *et al.* (1981) present a brief description of various statistical models used for this purpose along with their strengths and weaknesses.

Water Management Objectives

Before reservoir operations can be reevaluated, clear water management objectives must be defined. Identifying relevant planning objectives, and defining the relative importance of each of these objectives, is one of the most difficult aspects of water resource systems planning (Loucks *et al.* 1981). Many individuals and groups are affected by reservoir operation, and therefore the decision making process is inevitably pluralistic. When planning for new water projects, government agencies have considered trade-offs between such objectives as economic growth, regional development, regional autonomy, resource development, environmental quality, employment, population control, agricultural self-sufficiency, foreign trade, national security, energy dependence, and public health. Traditional water uses for multiple purpose reservoirs

include flood control, hydro power, navigation, municipal supply, irrigation, recreation, power-plant cooling, waste disposal, and waste assimilation. Recent demands include more environmentally oriented uses such as endangered species, anadromous fish, wildlife, riparian habitat, and water quality. Until recently, most studies involving water management objectives were done to explore possible construction of new projects. Now, techniques are needed to evaluate benefits for each use as it relates to reservoir operation. These techniques should include some quantitative representation of each objective to allow comparisons between alternatives.

To evaluate changes in reservoir operation motivated by conflict, water management objectives can be defined in three phases. First, each interest group should state their goal clearly. Secondly, the stated goal must be written in terms of specific reservoir operation parameters (a function of storage, release, or flow). Finally, the analyst must create a mathematical statement of each objective. This mathematical statement allows simulation and optimization models to evaluate and compare alternative reservoir operating plans according to their performance (USACE 1991c).

For example, consider a group interested in preserving an endangered species of fish that lives in a stream below a reservoir. Their general goal might be to "Protect and promote recovery of the endangered fish." More specifically the goal could be to "Increase the species' population by 5% over the next three years in the five mile section of stream below the reservoir." Although this goal is understood, it is not useful as a water management objective in this form. A useful water management objective must specify tangible reservoir operational patterns that could help meet the goal of "protecting and promoting recovery." An example of a useful objective statement is: "Maintain the temperature of the stream between *X* and *Y* degrees within five river miles downstream of the dam." This objective statement allows the analyst to determine how the reservoir could be operated specifically to support the goal of "protecting and promoting recovery" of the endangered fish.

Another example goal is to "Maximize recreational opportunities on the lake." Again, although easily understood, the analyst does not have enough quantitative information to determine how reservoir operational alternatives affect this goal. A useful statement of the objective would resemble something like: "Maximize the number of days the reservoir level is between *X* and *Y* feet during May through September."

Beyond the verbal description of the water management objective related to reservoir operations, the objective needs to be quantified to allow analytical comparisons between alternatives. Until recently, most water resource planning objectives have been evaluated for new water projects. The primary technique for quantifying these objectives is economic valuation through "willingness to pay" (Howe 1971; Loucks *et al.* 1981). These evaluations typically are insensitive to small changes in operational strategy. Recent demands for reevaluating existing reservoir operations require comparison of benefits resulting from small changes in operating policies. According to Wurbs (1993), the two approaches for quantifying changes in utility for water objectives related to operational changes include economic analysis (designed specifically to capture changes in the economic value of water uses due to operation)

and yield versus reliability relationships (USACE 1991c). An example of economic analysis applied to quantify benefits of water use on the Columbia River System is presented by the Institute of Water Resources (USACE 1993a). The most significant limitation of this method is that some objectives, (such as endangered species, riparian habitat, and scenic values), cannot be readily represented in economic terms. The risk versus reliability performance measures described by Wurbs are useful for evaluating model results, but cannot be used directly to formulate a mathematical objective function necessary to apply an optimization model. This report presents a method to create a quantitative objective function for each water use that does not require economic analysis.

Existing constraints

In addition to hydrology and objectives, a model must include reservoir system constraints. Constraints can be of two types. One type describes an actual physical limitation that cannot be violated at any cost such as conservation of mass. Other physical limitations can be overcome usually only at great cost and only in the long term, such as storage or release capacities. The second type, referred to as a *soft* constraint, can be viewed as an implicit objective or goal that could be violated, although the cost for violating the goal might be quite high. Examples of soft constraints include legal restrictions, contracted water deliveries, and budgetary limitations. When these implicit goals are represented as mathematical constraints, all feasible solutions must satisfy these conditions, making the model less flexible. If the soft constraints are represented as objectives, the model formulation is flexible since constraints do not have to be satisfied perfectly. If the soft constraints are not satisfied, other uses may produce sufficient benefits to offset the steep penalty of violating the constraints. Typically, mathematical constraints should be limited to those physical constraints that cannot be violated at any cost or only in the long term. This type of model formulation is more robust and also can provide insight to potential long term changes that should be sought to improve total system operation.

2.2 Quantify Objectives

Quantifying values of different water uses is essential for optimization modeling, and is usually the most difficult step. Previous studies performed by the Hydrologic Engineering Center (HEC) using optimization models employed economic objective functions (USACE 1991a; 1991b). Economists worked extensively to assign monetary values for every use being considered at each reservoir and related river reach. This approach is effective for traditional uses such as flood control, hydropower, irrigation, and recreation where widely accepted economic methods exist. However, economic valuation is more controversial for environmental objectives such as endangered species preservation or riparian habitat restoration. Methods to economically value environmental performance have proven elusive (Smith 1989). The availability of economic expertise can also limit economic valuation of uses for small reservoir systems. For the large reservoir systems (Missouri and Columbia) previously studied using the HEC Prescriptive Reservoir Model (HEC-PRM), experienced economists familiar with the system were available to perform this monumental task (USACE 1993a).

Since optimization models rely on mathematical programming techniques, water use values must be expressed as mathematical functions with particular characteristics. Typically,

the objective functions used with the model must be convex. Obviously, complex value functions for water uses cannot be explained exactly by simple mathematical functions. However, this report assumes that all that is required in this context is to establish a function that permits reasonablecomparisons between uses. The following section presents a systematic procedure for developing value functions that does not require economic analysis.

The optimization model used for the case study (HEC-PRM) requires that water use values be represented via penalty functions. Penalty functions are essentially inverse value functions; the point of maximum value (utility) can also be expressed as the minimum penalty (cost). In subsequent discussions, water use values are expressed quantitatively as penalty functions. The technique for creating a numerical representation of water values is referred to as the Relative Unit Cost (RUC) Method. Unlike the economic approach of constructing penalty functions (USACE 1993a), penalty functions constructed using the RUC Method are relative rather than absolute.

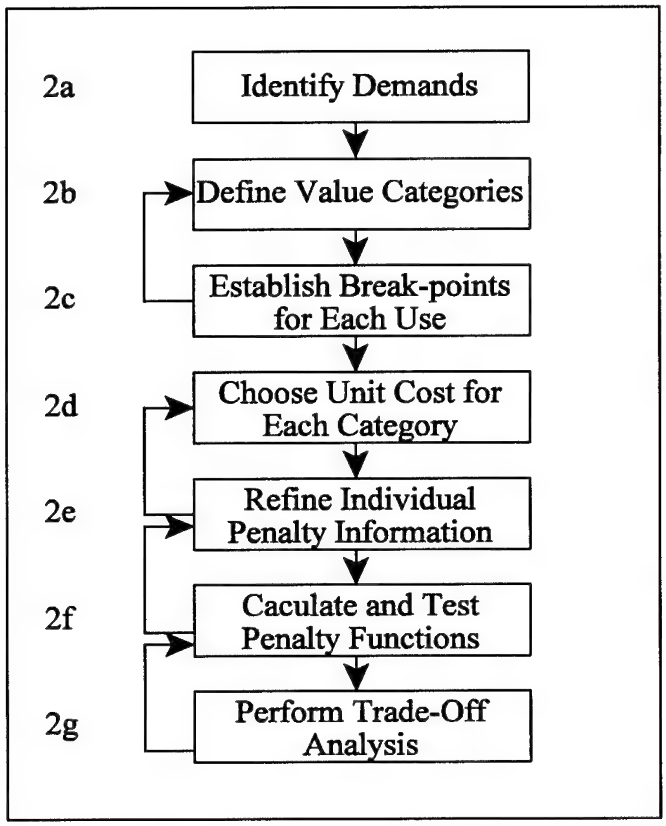

Figure 2.2 Steps in Relative Unit Cost Method

Penalty values computed for a given magnitude of flow or storage have meaning only when compared to other penalties for the same system. Penalties derived with the Relative Unit Cost Method are sufficient for comparing water uses on a reservoir system, but the penalty values cannot be used to make comparisons with other reservoir systems. Figure 2.2 diagrams the steps necessary to implement them RUC Method. The diagram shows the process is intended to be done iteratively until the penalty functions represent the actual water use values with acceptable accuracy. The level of required accuracy must be determined by the analyst with feedback from the advocacy groups.

Step 2a: Identify Demands on the System

The first step in the RUC Method requires identification of the demand for each water use served by the reservoir system. Along with the demands, the groups advocating each use also should be identified. These groups will provide much of the information needed to analyze reservoir system operation in light of the conflicting demands. (Much of this information should have been collected in the data gathering step). Once the demands and their advocates are identified, common value definitions need to be established to allow the various groups to communicate meaningfully with the analyst.

Step 2b: Define Value Categories for Each Use

Values for each use must be associated with a physical aspect (storage or flow) of the reservoir system to reevaluate reservoir operation. Utility gained from reservoir operation needs to be defined over the range of possible storages or flows for each use. To simplify quantification of value realized by each use from alternative reservoir operations, the benefits can be divided into generalized *value categories*. These value categories refer to ranges of advocacy group preferences. By determining to which value category different magnitudes of storage and flow 20 correspond, the range of storages and flows can be divided into *value regions*. These value regions refer to that set of storages or flows that produce benefits for a particular use that fall within a given value category (or advocate preference). The number of categories necessary for sufficient resolution of value definition may vary between systems, but three categories seems a reasonable place to start.

Figure 2.3 shows an example of how benefits for one particular use related to reservoir storage could be divided into five regions according to three value categories: *Ideal*, *Acceptable*, and *Adverse*. These general value categories provide advocacy groups with a common framework to specify their goals in terms of physical reservoir operational parameters and a few general levels of preference.

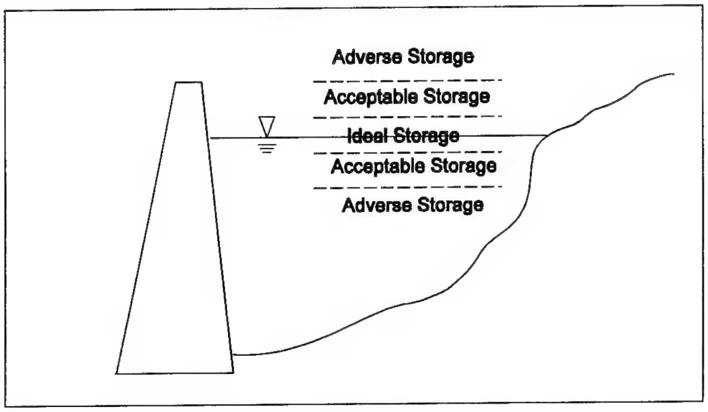

Figure 2.3 Example Value Regions for Reservoir Storage

Step 2c: Identify Storage or Flow "Break-Points"

Specific magnitudes of flow and storage that delineate the value regions for each use need to be identified. For the RUC Method, the flow or storage quantities that define the value region boundaries are called *value break-points*. To illustrate how value categories and break-points are used to help quantify objectives, consider recreation on a multiple purpose reservoir. The aim is to find those points in the operation of the reservoir where the quality or value of lake recreation changes significantly as represented by the chosen value categories. Recreation on the reservoir (as opposed to the stream) depends primarily on storage levels. As the amount of water stored in the reservoir changes, the elevation of the lake surface changes. Since much of the recreation activity on the lake depends on facilities around the lake perimeter (boat ramps, docks, etc.) the level of the lake surface is a key factor of lake recreational value. Therefore, a good way to establish value break-points for reservoir recreation would be to determine how lake surface elevations impact the use of access structures such as boat ramps. Table 2.1 lists elevations (storages) that delineate five value regions based on three value categories. The value categories were defined to mean:

- *Ideal* -- the range of storages or flows that provides the most utility for the advocated use (The advocacy group is content).

Table 2.1 Example Break-points for Reservoir Recreation Use

Value Region	Storage Range (KAF)	Elevation Range (ft)
Adverse	239.7 to 1451.3	1,144 to 1,265
Acceptable	160.5 to 239.7	1,125 to 1,144
Ideal	124.8 to 160.5	1,115 to 1,125
Acceptable	65.5 to 124.8	1,094 to 1,115
Adverse	0 to 65.5	990 to 1,094

- *Acceptable* -- the range of storages or flows that provides moderate utility for the advocated use (The advocacy group can tolerate the level of benefits produced but would prefer to operate in the *Ideal* region).
- *Adverse* -- the range of storages or flows that reduces benefits for the advocated water use by unacceptable amounts (The advocacy group strongly opposes operation in this region for long periods).

Based on these categories and their definitions, the reservoir recreation advocacy group can identify reservoir levels that delineate the value regions. For the hypothetical case (Table 2.1), consider the following scenario:

- The *Ideal* storage region is between 124.8 to 160.5 KAF due to the accessibility of two well developed boat ramps and an unpaved boat launching access. This facilitates easy access to the popular water sports areas.
- The *Acceptable* storage regions include 65.5 to 124.8 and 160.5 to 239.7 KAF. As the storage drops below 124.8 KAF or rises above 160.5 KAF, access to one of the developed boat ramps is hindered. This causes a reduction in water craft access to the lake and therefore decreases recreational use.
- The *Adverse* storage region could represent inaccessibility of all developed boat ramps.

According to the break-points given in Table 2.1, Figure 2.4 maps the reservoir storage value regions for recreational use according to the value categories. Qualitative value statements can be inferred from this map. For instance, Figure 2.4 shows that if the reservoir is operated around 200 KAF the recreation benefit for this example reservoir would be less than if it was operated around 150 KAF. However, at this point, the map does not offer any information regarding quantitative differences between benefits when operated near 150 KAF as compared to 200 KAF. Once value regions have been identified, the concept of unit cost can be applied to calculate penalty values for all possible storages or flows (Step 2d).

The analyst should be aware that this part of the model formulation can be both time consuming and costly. Gathering data to identify how reservoir operation impacts each desired use can require a great deal of work on the part of the advocacy groups (since the advocacy

groups and others may not know how reservoir operation affects their desired use). However, if the qualitative definitions are not done adequately, the penalty functions will not be useful. (This is true for economically based penalty functions as well.) A good example of this "mapping" process can be seen in the work done by the Bill Williams River Technical Committee (BWRCTC 1994).

Note: Defining value categories (Step 2b) and identifying break-points (Step 2c) are interrelated. (Both steps serve to define the value regions.) Some analysts may find it easier to identify critical value break-points for each use and then designate value categories later according to the number of break-points.

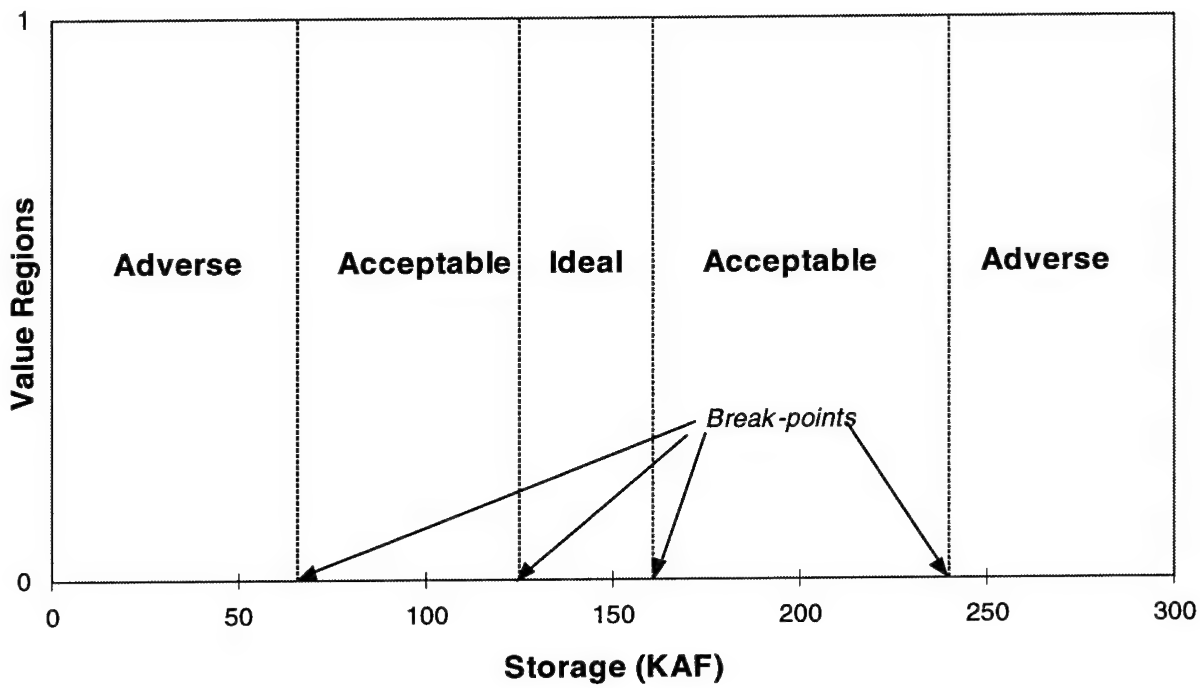

Figure 2.4 Map of Storage Value Regions for Example Reservoir Recreation

Step 2d: Apply Unit Cost Strategy for Value Categories

Identifying the value regions (ranges of physical parameters with constant value) for each use provides only half of the information necessary for a mathematical value function. The analyst must now supplement the qualitative information with quantitative value information. When using economic techniques for this part of penalty function development, economists typically determine the maximum possible economic benefit when the reservoir is in the *Ideal* region and then estimate the cost (revenue lost) for operating the reservoir at points outside this region. Non-economic penalty functions can be constructed following a similar strategy. A

systematic method using relative unit costs can be used to create penalty values at points throughout the defined value regions.

Two questions must be answered to formulate numerical value functions for use with an optimization model:

1. How do benefits (penalties) change for each use as the reservoir system operation moves away from the *Ideal* value region?
2. How do the benefits (penalties) from each water use compare to one another?

To answer the first question, the penalty for the *Ideal* region must be defined. Since the *Ideal* region represents the best value that can be realized for the use being considered, both the unit cost and the actual cost are zero within the *Ideal* region. In fact, the definition of value categories implies that the utility or benefit for a particular use is constant over each value region. Therefore the value function can literally be represented as a step function such as the one in Figure 2.5. Although the step function accurately represents benefits as defined by value categories, it cannot be used directly with linear programming models. The objective function must be convex (continuous with increasing slope) in order to find an optimum solution with linear programming. Thus, if the analyst wants to take advantage of linear programming optimization models, the value function must be edited to an acceptable form.

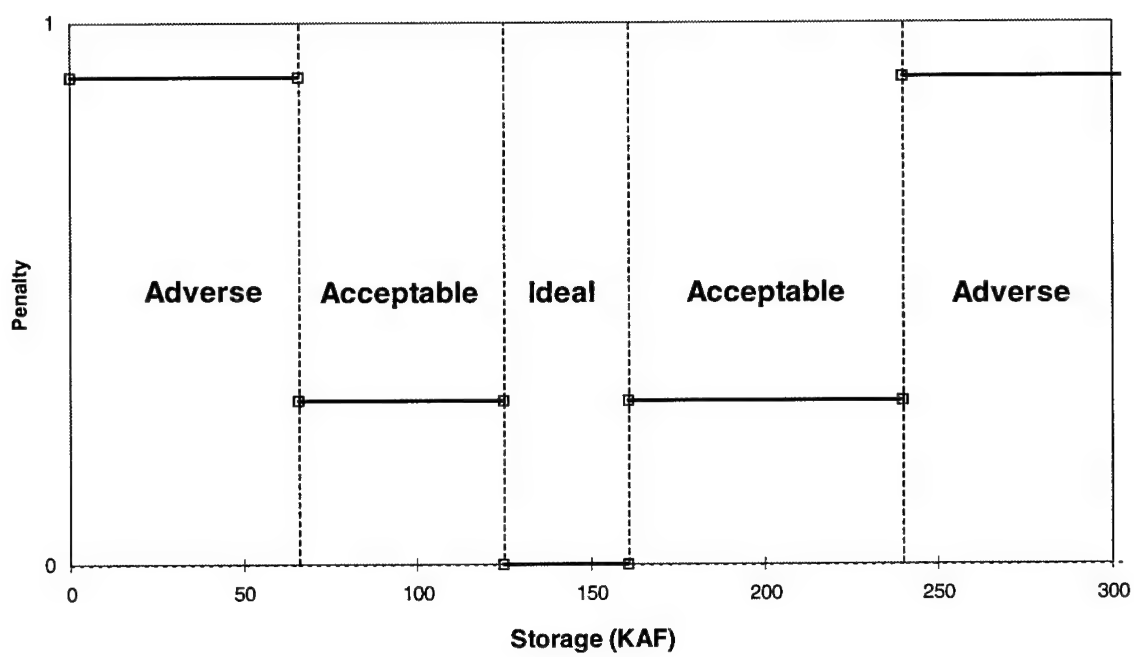

Figure 2.5 Value Function Represented as Step Function for Value Categories

The task of representing the value function using a convex function can be done several different ways. One reasonable approach would be to assign specific penalty values that are constant for each value category, and then edit the function as necessary to make it convex. The major difficulty with this method is the editing process to make the function convex while still representing the water use values adequately. Figure 2.6 shows three simple ways to describe the discontinuous penalty function as a continuous function. The first method listed in Figure 2.6 approximates the function by connecting the "outer" break-points (those furthest from the *Ideal* region) for each value region. The second method shown connects the "inner" break-points, and the third connects those points in the value region that bisect the two endpoints for that value region. Each of these approaches are *reasonable*, but all introduce undesirable effects. A major disadvantage of this method is that even after using this method to approximate the step function as a piece-wise continuous function, the function is not necessarily convex and usually must be edited further. Each phase of editing requires the analyst to make judgements regarding the reasonableness of each approximation.

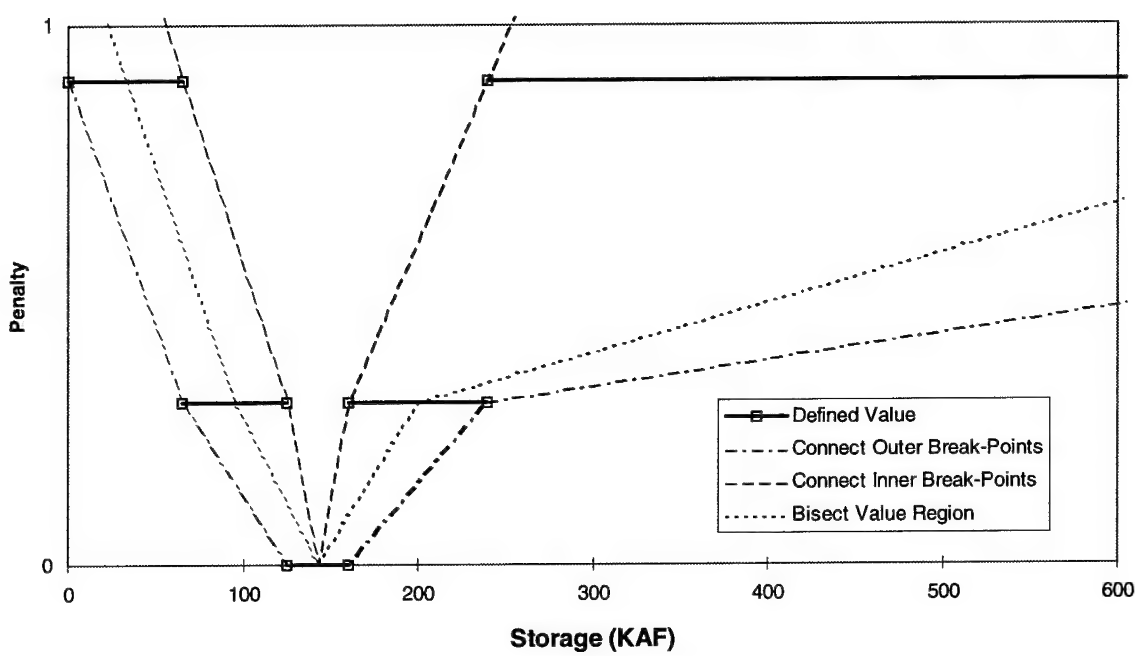

Figure 2.6 Three Approaches to Approximate Step Function as Piecewise Continuous

One way to avoid some of the problems stemming from convexity is to represent the penalty function by specifying a slope (unit cost) for each value region rather than a specific penalty value. This approach produces a convex function directly for most uses and reduces the amount of "adjustments" the analyst must make to fulfill convexity requirements. However, a disadvantage of specifying unit costs directly is that the resulting penalty quantities will not necessarily be equal at the boundaries of similar value regions (such as the two boundaries between *Acceptable* and *Adverse* in Figure 2.7). This difference in penalty magnitude for the

value region boundaries will be most pronounced for uses where the value regions are highly asymmetrical about the *Ideal* region.

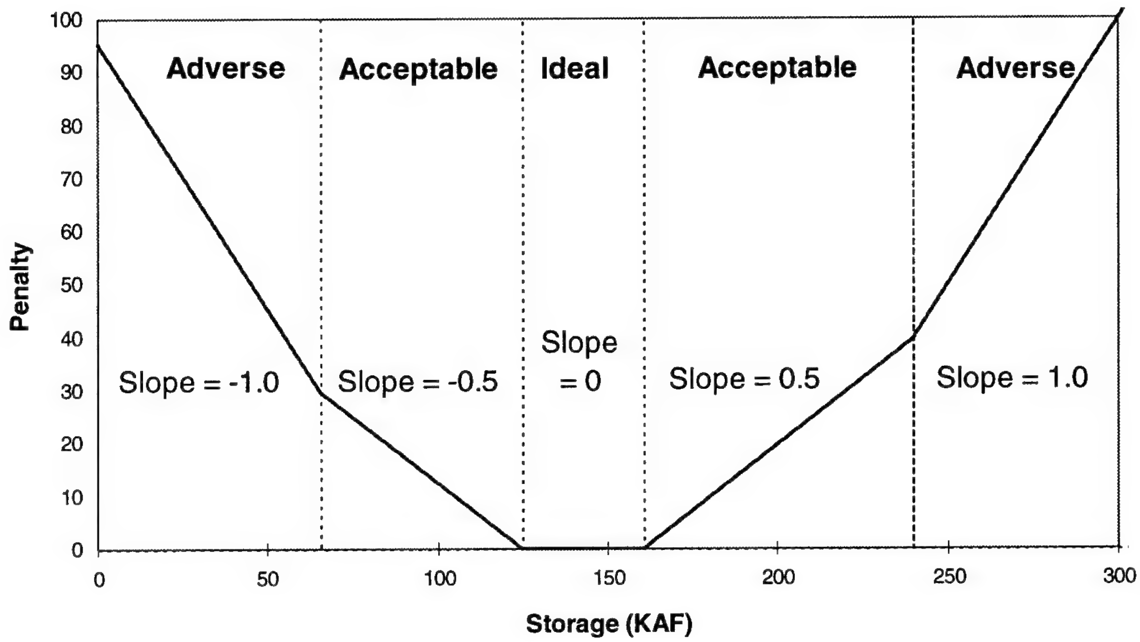

Figure 2.7 Penalty Function Using Unit Costs of 0.0, 0.5, and 1.0 for Value Categories

This report presents the tasks necessary to use relative unit costs (slopes) to develop value functions for each water use, but this approach may not be the best choice for representing values for water uses on all reservoir system studies. The approach that specifies relative penalty values for each value category to construct value functions may be better in some cases. The overall modeling strategy proposed should be relevant for most situations where technical information is needed to resolve conflict over reservoir operation, but the analyst must consider the strengths and weaknesses of the two value function quantification methods and choose the best method for each particular problem. In choosing which method is better for a particular study, the analyst should remember that the optimization model serves only as a screening tool for more detailed simulation studies, and therefore does not require extremely precise value formulations (and often the values for water uses are not known with great certainty anyway). The computerized penalty function generating tool developed for this work supports both approaches (see Appendix B).

Since the RUC method is not intended to produce absolute penalty values (such as economic values), the magnitude of unit costs for a value category is unimportant except in relation to the magnitude of unit costs for other value categories and uses. This premise is key to the success of the RUC Method. The analyst can create penalty functions with the information gathered by defining meaningful unit cost *ratios* between value categories and uses. At this

point in the process, the unit costs for the same value category among different water uses is initially assumed to be equal. This assumption is made to facilitate the initial penalty definition (its validity will be discussed later). The analyst must now choose magnitudes for the unit cost for each general value category. When trying to choose initial magnitudes it is best to keep the formulation as simple as possible. Perhaps the easiest way to explain this process is through example.

Figure 2.4 shows that the range of possible storages for the hypothetical reservoir is divided into five distinct value regions specific to recreation benefits. The analyst now tries to represent how the recreational benefits change when the reservoir is operated in these different regions. For the first attempt at describing the recreation penalty function for the hypothetical reservoir (data in Table 2.1 and Figure 2.4), unit costs are chosen to be 0.5 in the *Acceptable* region and 1.0 in the *Adverse* region. (By definition the unit cost is zero everywhere in the *Ideal* region). Figure 2.7 illustrates the resulting penalty function when calculated for the chosen unit costs. These unit cost magnitudes can be interpreted to mean, "As reservoir storage deviates outside the *Ideal* region into the *Acceptable* region, a penalty of 0.5 units is realized for each KAF of change." If reservoir storage deviates from the *Ideal* region sufficiently to reach the *Adverse* region, each KAF deviation beyond the *Acceptable* region adds 1.0 unit to the penalty. Further interpretation of these chosen unit cost magnitudes implies that the penalty assessed within the *Adverse* region occurs at twice the rate as when in the *Acceptable* region. This ratio of unit costs between value regions needs to be established in cooperation with each advocacy group. Since the resulting penalty functions are used only to compare different alternatives through a mathematical programming algorithm, the ratios do not need to be exact. Instead, the ratio relationships need only be accepted as reasonable by the interest groups.

Again, the choice of unit cost values are only important in relation to one another. For instance, in the previous example, unit costs of 1.0 and 2.0 (Ratio = 1/2) could be used in place of 0.5 and 1.0 (Ratio = 1/2) with no change in functionality. However, if values of 0.5 and 0.75 (Ratio = 1/1.5) are used, the implication is significantly different. The ratio of unit costs needs to be selected to reasonably represent the actual change in utility realized as reservoir conditions change. For simplicity, the value categories should be chosen so that one set of unit costs can be applied for each use. In other words, if unit costs of 0.5 and 1.0 are used to calculate penalty values while in the *Acceptable* and *Adverse* regions for recreation, the same unit costs should be applied for the other uses (such as flood control or conservation) on the reservoir. Obviously, the break-points that delineate where the value regions start and stop for each use will be different, but the unit cost for each region should be kept consistent between uses (under the initial assumption that all uses are of equal value).

Step 2e: Refine Penalty Information for Each Water Use

The previous exercises yield a "rough" penalty formulation (as shown in Figure 2.7) for each water use being considered. Now the penalty functions should be refined by addressing two issues:

1. The region of zero slope in the *Ideal* region, and
2. Important value changes for some uses not represented by the broader value regions.

Penalty functions with a segment of zero slope can lead to instability in the numerical methods for problem solution and should be avoided. Fortunately, this problem is not difficult to avoid. In reality, water users are seldom truly indifferent regarding a range of operational parameters even though all points within that range yield the same real benefits. Therefore, the task at hand is to determine which *point* in the *Ideal* region the advocacy group would prefer if given a choice.

Take the hypothetical lake used for recreation as an example. The data provided (in Table 2.1) implies that no significant difference exists for lake recreation between storages of 124.8 and 160.5 KAF. However, if recreation advocates for this lake are asked to specify their preferred *point* of operation within the *Ideal* region, they most likely would have a preference. They might prefer to keep the reservoir as full as possible while staying within the *Ideal* region. The process used to represent these slight preferences within the penalty functions is called *biasing*. Typically, the unit costs assigned to represent these subtle preferences should be at least an order of magnitude smaller than the smallest unit cost assigned for the general value categories. For the hypothetical reservoir example, a bias unit cost of 0.001 would be reasonable to represent this slight difference in preference within the *Ideal* region.

The second issue to consider when refining penalty functions is to represent important fine preference gradients within the larger value regions. For instance, it is possible that most water uses can be sufficiently represented using three value categories, while one or two of the uses require more break-points to capture the real changes in benefit realized as operational parameters change. The additional value regions can be added by subdividing the general value regions and assigning unit cost magnitudes between those specified for the earlier regions. This should only apply to a small percentage of the uses. If the number of value regions must be adjusted for several uses, the number of general value categories should probably be revised to provide a finer resolution of advocate preference.

One potential pitfall with the Relative Unit Cost Method stems from biasing and must be carefully avoided. Because the method utilizes unit costs to define penalty values for differing uses instead of actual costs, the implication of penalty functions can be misleading between uses. The key area of concern arises when comparing storage related penalties and flow related penalties. Since potential changes in flow tend to be small when compared to the range of possible reservoir storages, biases placed on storage-related penalties can actually overshadow penalty values for flow-related goals. Furthermore, a unit of water kept in storage can "accumulate" penalties over time (see Israel 1996). Therefore, the analyst must insure that the maximum possible penalty due to biasing is always smaller than the minimum possible penalty for all other uses within that same value category.

Step 2f: Calculate and Test Penalty Functions

The final step in the RUC Method involves calculating actual penalty values at all break-points for each individual use. Since the penalties are described by constant unit costs between these points, penalty values at the break-points are sufficient to describe the entire penalty function. Also, because the penalty functions are constructed using general information, each penalty function representing the individual uses should be tested. Then to solve for system

operation considering all uses, the analyst must combine the individual use penalty functions that apply to the same reservoir or river reach. This combination of individual penalty functions is called a *composite* penalty function.

Once break-points (independent variable) and unit cost magnitudes (slope) have been defined for all uses, calculation of the penalty values (dependant variable) is straightforward. Nonetheless, these simple calculations become quite laborious when repeated many times. The work necessary to create composite penalty functions can be particularly time consuming. To make this process less onerous and more reliable, a computerized pre-processor utilizing a graphical-user interface was created to aid in constructing individual and composite penalty functions, as described in Appendix B.

Another important consideration when calculating penalty functions is convexity. The mathematical conditions that allow for an "optimum" solution using HEC-PRM require that all penalty functions be convex. Therefore, each penalty function should be tested for convexity. If the functions are not convex, they must be edited to be made convex. The U.S. Army Corps of Engineers Hydrologic Engineering Center developed a program called PENF to facilitate making piecewise linear functions convex (USACE 1993b).

After penalty functions are calculated for each water use, they should be tested. The recommended test procedure involves running HEC-PRM for each use as if it were the only demand on reservoir operation. The results for each run should represent the mathematically "optimal" reservoir system operation for that use over the analysis period. The analyst can then scrutinize the results to determine if the penalty functions for that use produce results consistent with expectations based on the verbal objective. For example, if the model is run for the hypothetical recreation scenario used before, the resulting reservoir storage levels should fall in the *Ideal* region a significant amount of the time. If the results show that the reservoir storage is consistently above the *Ideal* region, the analyst could deduce that the penalty functions are probably not representing the stated objective adequately. Since the optimization model is operating for only one purpose, resulting operations should be in the *Ideal* region unless there is too much or too little water introduced into the system to allow that to occur. Similarly, if analyzed for an objective that specifies an *Ideal* release region, and the results seldom match that region, the penalty functions for that objective should be reconsidered.

Step 2g: Preliminary trade-off analysis

Testing the penalty functions individually for each use produces another benefit. Once the analyst believes the penalty function adequately represents the stated objective, the HEC-PRM results for that purpose indicate the highest benefit that can be obtained for a particular use. These results can give the interest groups a good indication of the best they can hope for with respect to their advocated use since HEC-PRM made operating decisions based exclusively for that demand. Results obtained by operating for other objectives can also provide interest groups with an idea of the worst they could expect (i.e., if their objective were completely ignored). These preliminary results can be summarized in a "pay-off table," as shown in Table 2.2, which can quickly point out similarities and conflicts in operating for various objectives.

After testing and refining the unit cost specifications for each water use, the designation of relative value between the water uses should be revisited. This will be addressed in Step 4: Screen Alternatives.

Table 2.2 Example of Pay-Off Table

Criterion Optimized	A	B	C
A	0.1	1.0	2.0
B	1.0	0.2	3.0
C	2.5	3.5	0.3
Best	0.1	0.2	0.3
Worst	2.5	3.5	3.0

2.3 Set up Prescriptive Model

The Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) was used for the case study presented in this report. HEC-PRM is a deterministic optimization model which uses a minimum cost network flow algorithm (Jensen and Barnes 1987), along with an optimal sequential algorithm for incorporating hydropower (Martin 1983). Other reservoir system optimization models are also available for conflict resolution studies (USACE 1991c).

System representation

HEC-PRM requires that the reservoir system be represented as a network (a series of arcs and nodes). This typically requires some simplification of the actual system. Program documentation explains that "Goals and constraints on water allocation within the reservoir system can be represented in terms of flows along the arcs of a network. If a unit cost is assigned for flow along each arc, the objective function for the network is the total cost for flow in all arcs. The ideal operation will be that which minimizes this objective function while satisfying any upper and lower bounds on the flow along each arc while maintaining continuity at each node" (USACE 1991a). Basic constraints on this network include reservoir storage capacities, authorized pool allocations, release and spillway capacities, and the routing of water between reservoirs. HEC-PRM also allows the analyst to represent evaporation and direct withdrawals (such as irrigation pumping) from the lake, as well as losses (such as seepage) from channels.

Mathematical statement of problem

subject to:

$$\sum_{k \in M_O} f_k - \sum_{k \in M_T} a_k f_k = 0 \ (\textit{for all nodes}) \tag{1}$$

The optimization problem represented by a network with costs associated with flow can be written as follows (USACE 1991a, Jensen and Barnes 1987):

$$\textit{Minimize}: \ Z = \sum_{k=1}^{m} h_k f_k \tag{2}$$

$$l_k \leq f_k \leq u_k \quad (\textit{for all arcs}) \tag{3}$$

where:

m = total number of network arcs;
h_k = unit cost for flow along arc k;
f_k = flow along arc k;
M_O = the set of all arcs originating at a node;
M_T = the set of all arcs terminating at a node;
a_k = multiplier for arc k;
l_k = lower bound on flow along arc k; and
u_k = upper bound on flow along arc k.

Equations 1, 2, and 3 represent a special class of linear programming problem: the generalized minimum-cost network-flow problem. As mentioned earlier, HEC-PRM builds the objective function (Equation 1) from information regarding the value of water uses expressed in the form of penalty functions. These penalty functions provide a way to represent numerically the value associated with reservoir operation decisions for particular uses.

As seen in Equation 1, the numerical parameter of the penalty function actually used is the slope (h_k) at a given storage or flow representing the unit cost (rate of penalty assessed) as the independent variable moves away from its optimum value (minimum penalty). Since the unit cost (or marginal cost) is central to the expression and solution of the minimum network flow problem, it proves to be a practical basis to construct penalty functions (RUC Method).

2.4 Screen Alternatives

Once the optimization model is set up, the screening process can begin. The purpose of the optimization model is to generate promising alternatives that could improve system operation with regards to the current water management objectives. For the proposed modeling strategy, screening of alternatives is done by two mechanisms. The first level of screening is done by running the optimization model using composite penalty functions representing all water management objectives. The second phase of screening can be done using yield and reliability criteria.

Initially, all uses were assumed to be of equal value while creating the initial individual use penalty functions under the RUC Method. In reality, this initial assumption of equal value will not be valid for most reservoir systems. Therefore, if different relative values between water uses exist for the system being analyzed, the individual use penalty functions generated using the RUC Method need to be adjusted. This adjustment can be done using multi-objective programming techniques.

Multi-objective Programming

Various multi-objective programming techniques have been developed to address decision making problems that include several conflicting objectives. According to Cohon (1978), "Multi-objective approaches pursue an important decision making result: an explicit consideration of the relative value of project impacts." This type of analysis is necessary when the different objectives cannot be quantitatively represented using a single scalar unit (such as dollars).

Cohon (1978) classifies multi-objective programming algorithms into two categories: generating and preference techniques. The generating techniques emphasize development of information about a multi-objective problem that is presented to decision makers in a manner that allows the range of choice and the tradeoffs among objectives to be well understood. The preference techniques also generate alternatives, but they require that decision makers articulate their preferences and pass that information on to the analyst. Penalty functions created using the RUC Method are well suited for use with two particular multi-objective programming techniques. One is a generating technique (the "Weighting Method"), and one is a preference technique ("Prior Assessment of Weights"), and one is a hybrid approach ("Interactive Assessment of Weights").

The Weighting Method involves a systematic (automated) scheme of varying the relative weights of each objective (via their penalty function) to approximate a non-inferior set of operational alternatives for the reservoir system. (The non-inferior set is a collection of alternatives in which an improvement in one objective must come at a loss to another objective). Since the optimization model must be run multiple times to approximate the non-inferior set, this method may be computationally demanding.

The Prior Assessment of Weights technique is preferred, when feasible, because it is generally less computationally demanding than the Weighting Method. If value judgements (or

preferences) for the relative importance of each use can be obtained, much of the non-inferior set does not need to be generated.

The Interactive Assessment of Weights technique requires interaction between the analyst and the decision makers during the generation of results. Upon review of one set of model results (based on a particular set of weights), the decision makers re-assess the weights and suggest a new set for the next run. Although multiple runs of the optimization model are required, much of the non-inferior set may still not need to be generated.

It should be emphasized that each of these multi-objective programming techniques leads to exactly the same mathematical formulation. In each case, the RUC Method is modified simply by multiplying the unit cost for each value category by an appropriate factor and recalculating the corresponding penalty values. These techniques, however, are not without limitations. The three main limitations of the Weighting Method (or its variants, Prior/Interactive Assessment of Weights) are as follows:

1. In certain ranges, large changes in weights can lead to little/no change in the optimal solution.
2. In other ranges, small changes in weights can lead to large shifts in the optimal decisions.
3. For a non-convex feasible region, not all of the non-inferiority set can be generated.

Other multi-objective programming techniques, such as the ϵ-constraint method (Haimes and Hall 1974) or the reference point method (e.g., Makowski *et al.* 1996), overcome these limitations, but they are not amenable to a network flow programming formulation.

Running HEC-PRM with composite penalty functions generated according to one of the multi-objective programming techniques is the first step in the screening process. Each set of results for reservoir operations produced by the set of differently weighted penalty functions provides a promising alternative to consider further. This step quickly narrows down the huge (practically infinite) set of possible operation schemes to a range of alternatives most likely to closely meet the specified water management objectives. Nonetheless, if the Weighting Method is used, the resulting set of alternatives may still be too large to carry into the more detailed (and more costly) phase of simulation modeling. Therefore, another level of screening can be helpful.

Performance Measurement

This secondary level of screening relies on yield and reliability information. This process provides a measure of how well each alternative generated using the optimization model meets the specified objective for each use based on various performance measures. This requires post processing of the results according to predetermined criteria. For example, if the analyst is evaluating an alternative to see how well it meets the hypothetical reservoir recreation objective, the analyst might calculate the percentage of time reservoir storage was in each of the three value categories specified. Table 2.3 presents hypothetical reliability information for three alternatives generated using the optimization model. The results from the optimization model would be analyzed to produce the four statistics shown in the table. This example shows that Alternative 2 causes the storage to be in the Ideal region the most and in the Adverse region the least of the

three alternatives evaluated. This type of information can be compiled for each water management objective and all alternatives. The tabulated performance measures should be discussed with the advocacy groups to try to select a subset of these alternatives to explore further.

Table 2.3 Alternative Performance Comparison for Recreation Objective

Alternative Number	Mean Storage (KAF)	Percentage of Time Reservoir Storage in Value Region		
		Ideal	Acceptable	Adverse
1	123.2	36 %	49 %	15%
2	142.4	42%	48 %	10%
3	178.3	29%	54%	17%

2.5 Set up Descriptive Model

After the most promising alternatives from the optimization model results have been selected, the analyst needs to test and refine these alternatives using a simulation model of the reservoir system. In this, the analyst must consider much of the same information used to set up the prescriptive model. According to the needs of the study, the model may be set up to evaluate a smaller time step than the monthly interval used with HEC-PRM. If so, the necessary stream flow records and other relevant input data will need to be compiled. Also, due to the higher flexibility of most simulation models, some of the simplifications required for the prescriptive model construction can be eliminated. An important consideration when choosing a simulation model is the ability to enter operating rules in a flexible form (including Boolean logic and rules based on inflows, storage levels, season, etc). Since the aim of this phase of modeling is to infer operating rules from the HEC-PRM results and then test and refine these rules, this flexibility is of utmost importance.

2.6 Refine Alternatives

By this stage in the process, the advocacy groups should have selected a small number of promising alternatives to scrutinize. The first task is to deduce a set of operating rules based on information readily available to those operating the reservoir system that produces an operation pattern similar to that evident in the HEC-PRM results. Once a general form of operating rule is found, it can be refined using yield and reliability performance measures.

Infer Operating Rules

Deducing or inferring operating rules from HEC-PRM results is probably the most challenging task of this modeling strategy. Since HEC-PRM produces results based on a mathematical programming algorithm for a specified objective, the operational pattern will not necessarily follow a traditional operating rule format. Lund reviewed approaches for deducing operating rules from deterministic optimization model results (Appendix A of USACE 1992). Lund states that various approaches have been used that "seek to detect and substantiate a pattern in historical optimal operations that can be reduced to rules which are based on the reservoir operator's current state of knowledge. Thus, operation rules must be based on known states such as: the current month, current storage, and current or forecast inflows." The methodology used for the case study presented in this report falls under Lund's Intuitive Approach category, an approach successfully applied to the Missouri River system (USACE 1992; 1994a). A variety of graphical and statistical tools were used to analyze HEC-PRM results to identify and substantiate apparent patterns of operation. Descriptive statistics, histograms, scattergrams (data plots), and time series analysis were used to uncover possible rules.

Simulate Operating Rules

The general rule forms produced in the inference phase should be tested and refined using a simulation model. In essence, the suggested rules from the optimization results serve as a point of departure for more traditional simulation studies of operation plans. This phase can be used to evaluate suggested rules according to the following criteria: (1) their effectiveness in reproducing operational patterns evident in the optimization results, (2) their operational feasibility, (3) their improvement over existing rules, and (4) their performance under extreme scenarios.

Measure Performance

The types of yield and reliability information presented earlier can provide quantitative performance measures for each alternative to aid in testing and refinement of operating rules through simulation. These performance measures should be established first for current operations to provide a baseline to compare all alternatives, and then for the small subset of alternatives chosen from the optimization results.

2.7 Offer Alternatives for Selection

The purpose of the modeling exercise is to present a range of viable alternatives that can help the advocacy groups in conflict find an acceptable compromise. The analyst should keep this in mind when presenting results. The minimum amount of information should include a summary table of the performance measures for each alternative and water management objective. Various graphical representations could also be useful, such as comparative plots of time series of storages or releases for the different alternatives. Another useful presentation technique is a list of alternatives ranked according to the benefits produced for each objective.

2.8 Summary of Modeling Strategy

The modeling strategy proposed offers a systematic method to develop, screen, and evaluate reservoir operational alternatives to help resolve conflicts over water resources. The method takes advantage of an optimization model for screening and a simulation model for testing and refining alternatives. Optimization models require numerical representation of value for all water uses. Historically, most of these quantitative value functions have been formed using economic analysis. However, economic analysis is not always feasible for all water uses. Therefore, a systematic method that produces relative value functions was presented. This method provides an approximate representation of advocacy group preference towards specific modes of reservoir operation. These approximate value functions allow the analyst to benefit from the optimization model's screening capability to make the detailed simulation study more efficient. The series of steps proposed were used to perform the following case study.

Chapter 3

Case Study - Alamo Lake, Arizona

The operation of Alamo Lake, Arizona was evaluated to demonstrate the proposed modeling strategy and test the Relative Unit Cost Method. Alamo Lake is a multiple purpose reservoir owned and operated by the U.S. Army Corps of Engineers. Alamo Lake is located in La Paz and Mojave Counties in Arizona on the Bill Williams River approximately 40 river miles upstream of the confluence with the Colorado River. The reservoir has a maximum capacity of 1,451,300 acre-feet and serves a gross drainage area of 4,770 square miles with a mean annual runoff of 113,300 KAF. Average annual precipitation for the Bill Williams River Basin is 13 inches and average annual pan evaporation is 65 inches.

During the late 1980's, agencies responsible for managing the Bill Williams River and Alamo Dam and Reservoir experienced increasing conflict among their individual missions and perspectives. Much of the disagreement stemmed from how the Corps was operating the water conservation pool at Alamo Lake. In August of 1990 the agencies formed an interagency planning team to develop a comprehensive water resource management plan for the Bill Williams River corridor. Over the past four years the Bill Williams River Corridor Technical Committee (BWRCTC) thoroughly defined the competing demands related to reservoir operation. They then used a descriptive model (HEC-5) to evaluate alternative operational strategies intended to meet demands more effectively. The information gathered during this study was used to apply the optimization-simulation strategy, and the results are compared for the two methods.

3.1 Gather Data

The first part of the modeling process involves gathering relevant data. The BWRCTC gathered the necessary data (hydrology, water management objectives, and system constraints). The hydrology and system constraints were provided by the Los Angeles District U.S. Army Corps of Engineers Office. The water management objectives were defined in the BWRCTC report (1994). Table 3.1 lists the agencies represented in the Bill Williams River Corridor Technical Committee along with the water uses the agencies advocate.

The following list provides a description of the water management objectives listed in Table 3.1 (BWRCTC 1994):

- *Flood Control* -- The dam was authorized to provide flood control for lower Colorado River communities downstream from Parker Dam (Lake Havasu), and protect property along the Bill Williams River corridor. Alamo Dam is operated in conjunction with the U.S. Bureau of Reclamation dams on the Colorado River to reduce flood related damage.

- *Water Conservation and Supply* -- The entire water supply in the Bill Williams River (before reaching Lake Havasu) is entitled solely to Arizona. Bill Williams River flows that reach the Colorado River are allocated in a manner consistent with the "Law of the River" including the U.S. Supreme Court Decree in *Arizona v. California* of March 1964. To date, the Corps has not contracted with a water supply user for supply and conservation storage. The conservation pool has been used only for short-term storage of water, which has been released to Lake Havasu.
- *Recreation* -- The recreation pool was established immediately below the water conservation pool. The Arizona Game and Fish Department currently holds water rights for 25,000 acre-feet in the recreation pool. These rights are for fish, wildlife, and recreational purposes. The Arizona State Parks Department operates and maintains boat launching ramps, campgrounds, and appurtenant structures.
- *Fishery* -- Arizona Game and Fish has established a lake bass fishery. The survival of the fishery is most directly connected to fluctuations in lake levels during the spawning and growing season.
- *Endangered Species* -- Two pairs of Southern Bald Eagles, a federally listed endangered species, have been nesting around Alamo Lake since the early 1980's. In 1988 the U.S. Fish and Wildlife Service requested that the Corps maintain a minimum water surface elevation of 1,100 feet at Alamo Lake to ensure sufficient forage area for the eagles. The request was in accordance with the National Environmental Policy Act and the Endangered Species Act.
- *Wildlife Habitat* -- The Bill Williams River Corridor includes a National Wildlife Area and is home to various neo-tropical migratory birds and numerous endangered species. The wildlife habitat is most dependant on the vitality of the riparian habitat.
- *Riparian Habitat* -- The riparian habitat along the Bill Williams River contains the last extensive native cottonwood tree stands in Arizona. The U.S. Fish and Wildlife Service believes that a significant portion of the cottonwood trees have been destroyed due to the pattern of past Alamo Dam releases.

Table 3.1 Comparison of Results from Simulation Alone vs. Combined Approach

Objective	Criterion	Simulation	Combined	Compare
Recreation	% time WSE at or above 1090'	99.3	100	Better
	% time WSE at or above 1094'	93.6	100	Better
	% time WSE at or above 1108'	61.8	90	Better
	% time WSE between 1115' & 1125'	44.8	80	Better
	% time WSE between 1144' and 1154'	0.2	0	Same
	% time Outflow is between 300 and 7,000 cfs	3.2	0	Worse
	% time in March thru May WSE between 1115' and 1125'	48.4	80	Better
Conservation	Avg. Annual Evaporation in Acre Feet	16804	18646	Worse
Flood Control	Number of days WSE above 1171.3'	0	0	Same
	Max % of flood control pool used	0	0	Same
Wildlife	% time WSE at or above 1100'	78.2	100	Better
	Number of times from 1 Dec thru 30 June that WSE exceeds 1135' two or more consecutive days	12	0	Better
Fisheries	% time WSE between 1110' and 1125'	55.5	90	Better
	Avg daily release during June thru Sept	55	120	Better
	Avg daily release during Oct thru May	142	104	Worse
Riparian	% time WSE between 1100' and 1171.3'	78.2	100	Better
	% time releases >= 25 cfs in Nov thru Jan	75.6	19	Worse
	% time releases >= 40 cfs in Feb - Apr & Oct	79.8	30	Worse
	% time releases >= 50 cfs in May thru Sept	78.3	12	Worse
	No. times releases >= 1,000 cfs seven or more consecutive days in Nov thru Feb	15	0	Worse
	No. times releases >= 1,000 cfs seven or more consecutive days in Mar thru Oct	16	0	Worse

3.2 Quantify Objectives

Subcommittees of the Bill Williams River Corridor Technical Committee compiled separate reports with verbal descriptions of each water management objective. The information is well researched and documented (BWRCTC 1994). These reports also detail break-points for storage and flow established for each use according to three value categories. Based on the information in the BWRCTC reports, penalty functions were defined for each use following the Relative Unit Cost Method. These penalties were tested as proposed in the RUC Method description by running HEC-PRM exclusively for each objective. Appendix C presents the final penalty functions used for this study. Furthermore, the HEC-PRM results were compared for each water use to discern how the advocate groups' requests translated into reservoir operation. This type of evaluation provides some interesting insights into how different demands can impact reservoir operation. For example, for the Alamo study the resulting operation for riparian related use was particularly surprising. The stated goal of the BWRCTC Riparian Subcommittee is to:

> ... restore riparian resources downstream from Alamo Dam and maintain the cottonwood gallery forest at the upper end of Alamo Lake. The primary objectives for riparian resources in the Bill Williams River Corridor are 1) to maintain both area (acreage) and structural diversity of existing vegetation stands dominated by native riparian species, particularly cottonwood/willow stands, and 2) to expand coverage and diversity of native riparian through natural recruitment.

The subcommittee report also states, "A properly functioning riparian ecosystem could be restored by implementing a flow regime that mimics the pattern of historic (pre-dam) flows." However, when the penalty functions for riparian habitat interests were developed to produce the flow patterns specified in the report, the HEC-PRM results actually produced a release pattern quite different than the "historic (pre-dam) flows." Compare Figure 3.1, which shows a time series of unregulated monthly stream flows, and Figure 3.2, which shows the resultant monthly release pattern for Alamo Reservoir when operated exclusively to meet the demands of riparian habitat support and restoration. The flow results from HEC-PRM shown in Figure 3.2 approximate the requested flow pattern for riparian habitat maintenance and restoration well, but actually bear little resemblance to the pre-dam flows. These types of discoveries can be valuable both for the analyst and the advocacy groups.

HEC-PRM results give an idea of the best operation possible for each use (tempered by the simplifications required in forming convex penalty functions), and serve as a way to verify that the operational patterns requested by the advocacy groups produce the results they desire. The optimization results for each use also provide information to determine which demands conflict with one another. Figure 3.3 shows the storage time series determined to be optimal for each use. From this plot, it is clear that the fishery and recreation alternatives produce similar storage patterns. In contrast, the uses producing the most disparate storage patterns are the riparian habitat and flood control objectives. Figure 3.3 also shows that HEC-PRM utilizes nearly the entire range of reservoir storage (up to a maximum level specified by riparian interests) to produce a consistent and regular flow pattern (as seen in Figure 3.2). On the other hand, the flood control objective causes HEC-PRM to keep the reservoir as empty as possible to

allow attenuation of incoming flood peaks. This type of comparative information provides valuable insight regarding reservoir operation for multiple demands.

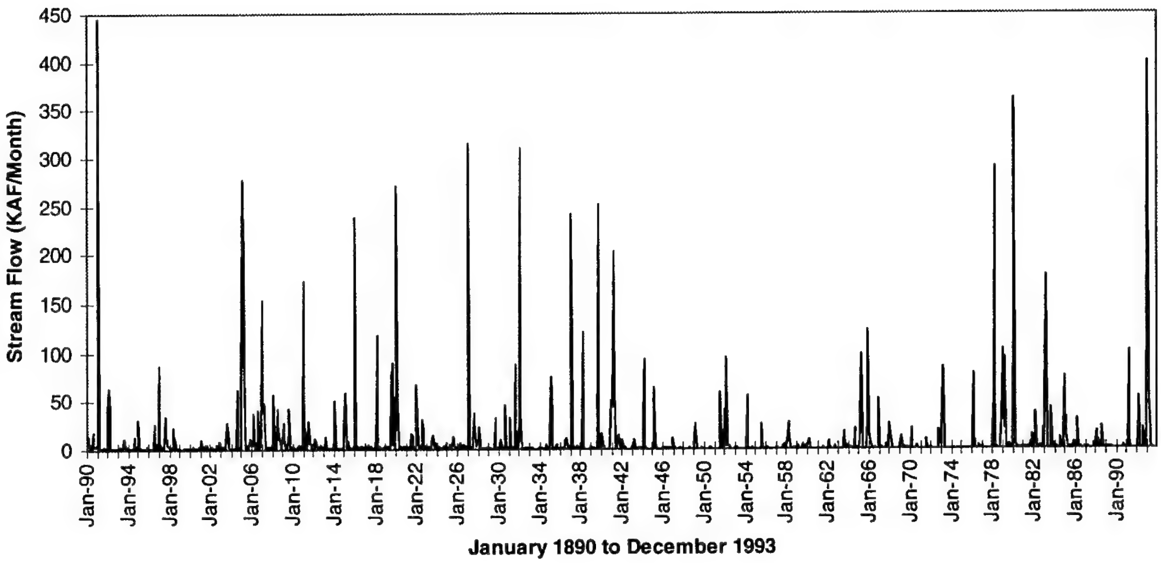

Figure 3.1 Historic (Pre-Dam) Stream Flows

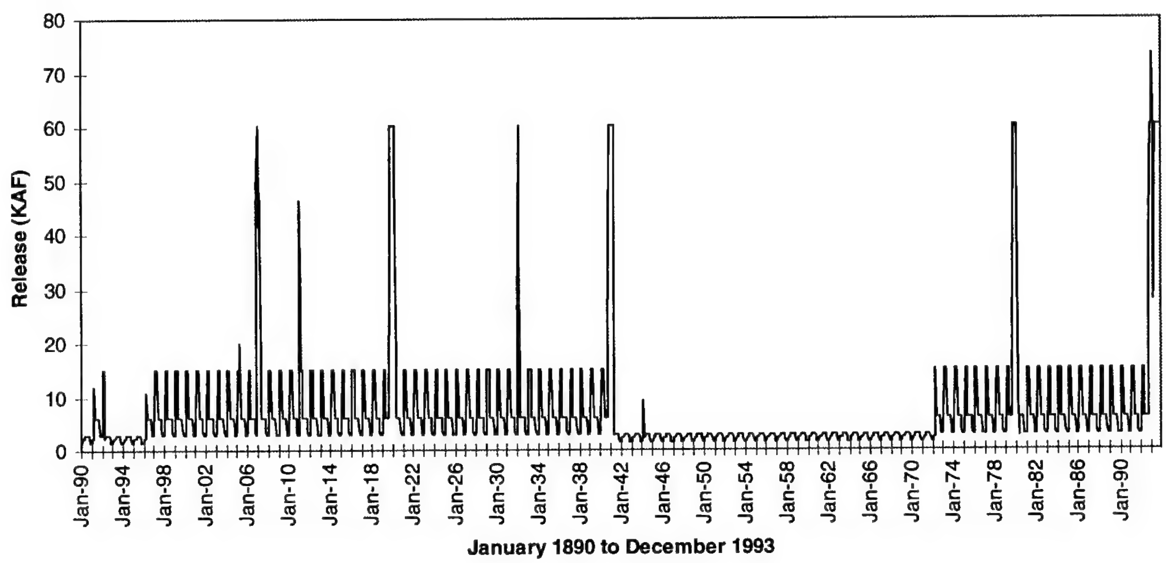

Figure 3.2 Monthly HEC-PRM Releases Based Strictly on Riparian Penalty Functions

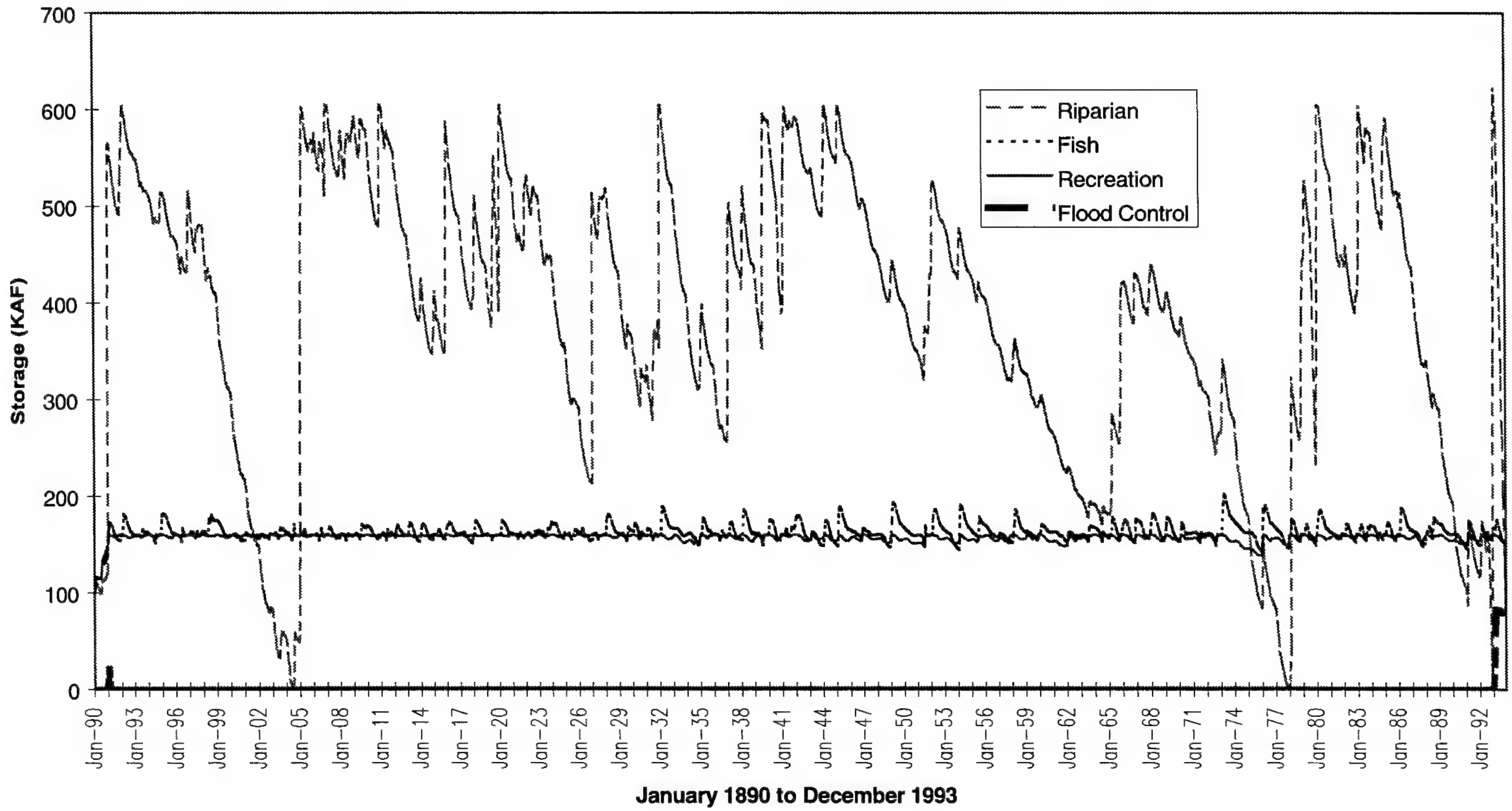

Figure 3.3 Comparison of Preferred Storage for Each Use

3.3 Set up Prescriptive Model

HEC-PRM generates optimal monthly reservoir operations according to specified water use values (or penalty functions), input hydrology, constraints, and initial and ending conditions. The input hydrology used for HEC-PRM is a historical record spanning 103 years of monthly inflows (January 1890 - December 1993) obtained from the Los Angeles District U.S. Army Corps of Engineers Office.[1] HEC-PRM was configured with the evaporation option using monthly evaporation rates provided by the L.A. District Office. Starting storage for each HEC-PRM run was set at 80.4 KAF to be consistent with the HEC-5 study conducted by the L.A. District Office. The only constraint added to the model was a minimum release of 10 cubic feet per second (cfs) required by Arizona water rights.

Due to simplifications required in formulating the problem for HEC-PRM, some specific objectives presented in the BWRCTC reports could not be represented. A primary example is the objective of limiting maximum daily fluctuations in lake level for fisheries. This objective could not be represented in HEC-PRM because the program can only consider monthly time steps. Another example is the objective to provide seasonal "flushing flows" to benefit the riparian habitat. These flows (intended to be high "pulse" flows that last for a few days) could not be explicitly represented in the monthly optimization model. These limitations were considered when inferring operating rules from the optimization results.

3.4 Screen Alternatives

Information provided by the BWRCTC indicated that it was reasonable to consider all water management objectives to be equal in value. Since this single case was adequate to demonstrate how to apply the proposed modeling strategy and test the RUC Method, further multi-objective analyses were not included in this report. Future research to develop support tools for applying the Weighting Method and Prior Assessment of Weights with HEC-PRM has been proposed. Since only one alternative was generated using HEC-PRM, the second phase of screening using yield and reliability information was not necessary at this step. Figures 3.4 and 3.5 display the pattern of operation that HEC-PRM determined to be optimal for the specified hydrology, constraints, and objectives. These results are scrutinized further in the refinement stage.

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[1] Note: Detailed review of the hydrologic record revealed that some inconsistencies may exist regarding the treatment of evaporation as it affects inflows. This potential discrepancy has been discussed with the Los Angeles District Corps office, and they are reviewing the hydrologic record.

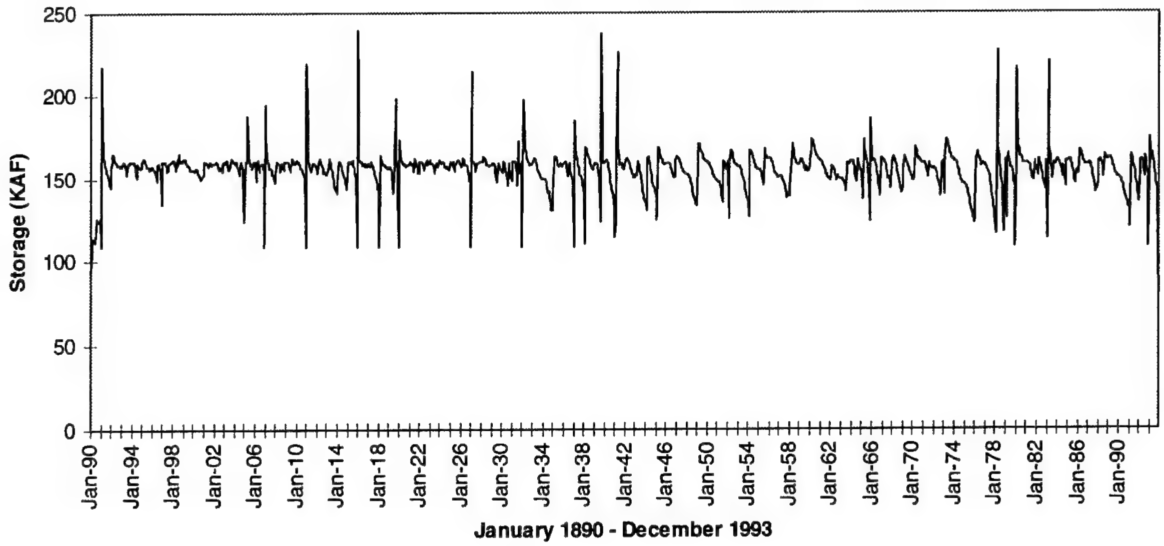

Figure 3.4 HEC-PRM Storage Time Series for Composite Penalty Function

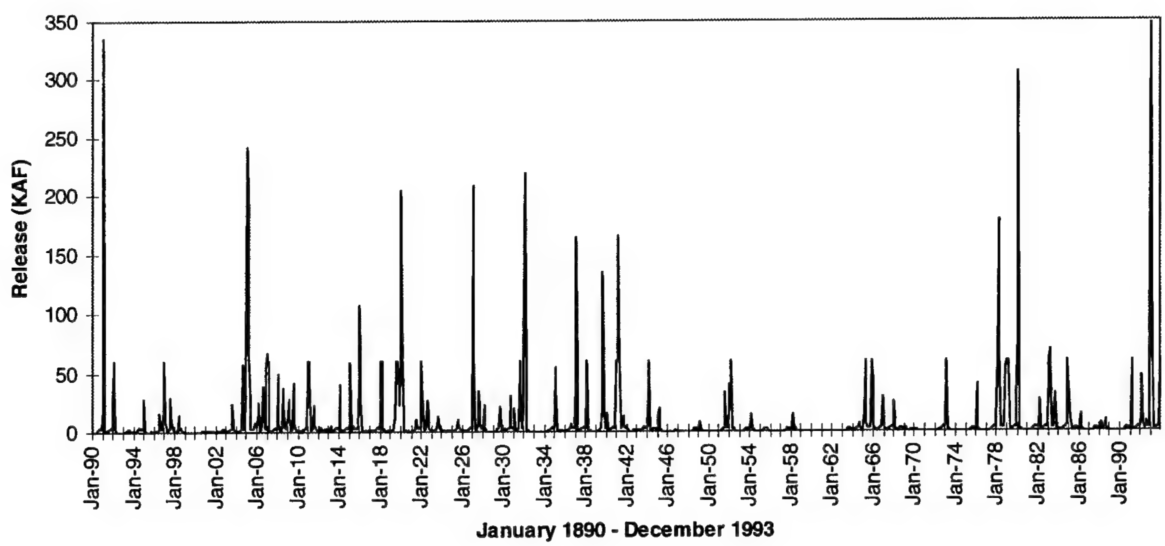

Figure 3.5 HEC-PRM Release Time Series for Composite Penalty Function

3.5 Set up Descriptive Model

To refine alternatives, a simulation model must be formulated to represent the system being studied. For this case study, Stella II (High Performance Systems, Inc.1993) was used to perform the simulation analysis. This modeling package was chosen because it allows for very flexible operating rule construction. The hydrologic input for the simulation modeling consisted of 64 years of daily inflows obtained from the Los Angeles District Corps office.

3.6 Refine Alternatives

To fully benefit from the optimization model, the analyst needs to determine a set of operating rules that can reproduce an operational scheme similar to the one found in the HEC-PRM results. In addition to the time series plots, descriptive statistics were generated for the storage and release results including percentiles and exceedance probabilities.

Figure 3.6 shows percentiles of storage by month for HEC-PRM results based on the composite penalty function. This plot illustrates that HEC-PRM resultant storages remain fairly constant throughout the year for most years (i.e., the trace of the 10th percentile and 90th percentile tend to be very near the median for most months). From this, it appears that the operating rule should be set up to maintain a fairly constant storage level throughout the year. The percentile plots for HEC-PRM releases indicate that releases are very low most of the time, but during a few months of the year the releases can be quite high (Figure 3.7). Because the releases tend to be very small at least 75% of the time, the previous deduction that the operating rule should be geared towards maintaining a set reservoir storage level is strengthened. Traditionally, release decisions are made according to changes in storage, or according to which authorized pool the reservoir is in. This approach could not be expected to work well if the goal is to maintain a target level.

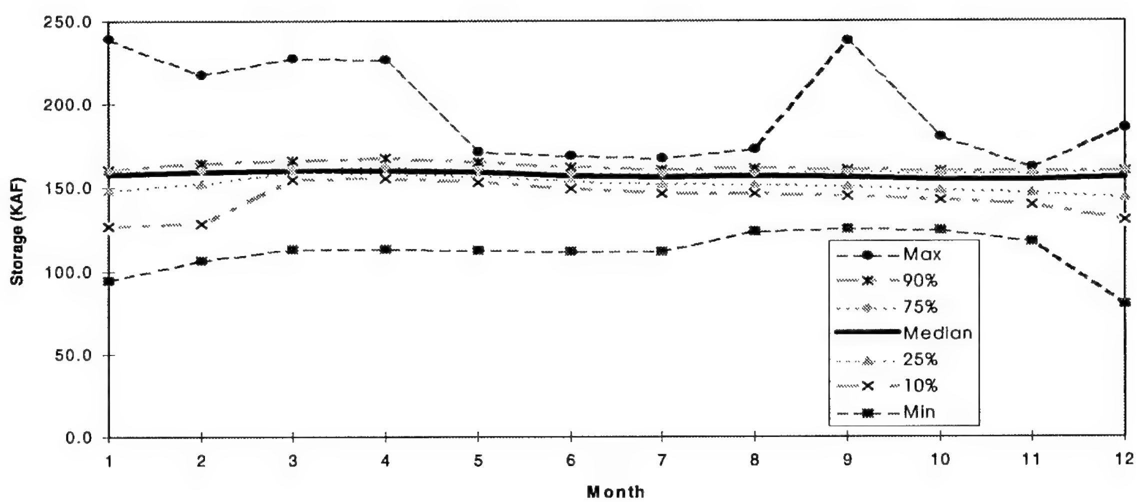

Figure 3.6 Percentile Plots for HEC-PRM Alamo Storage Results for Composite Penalty

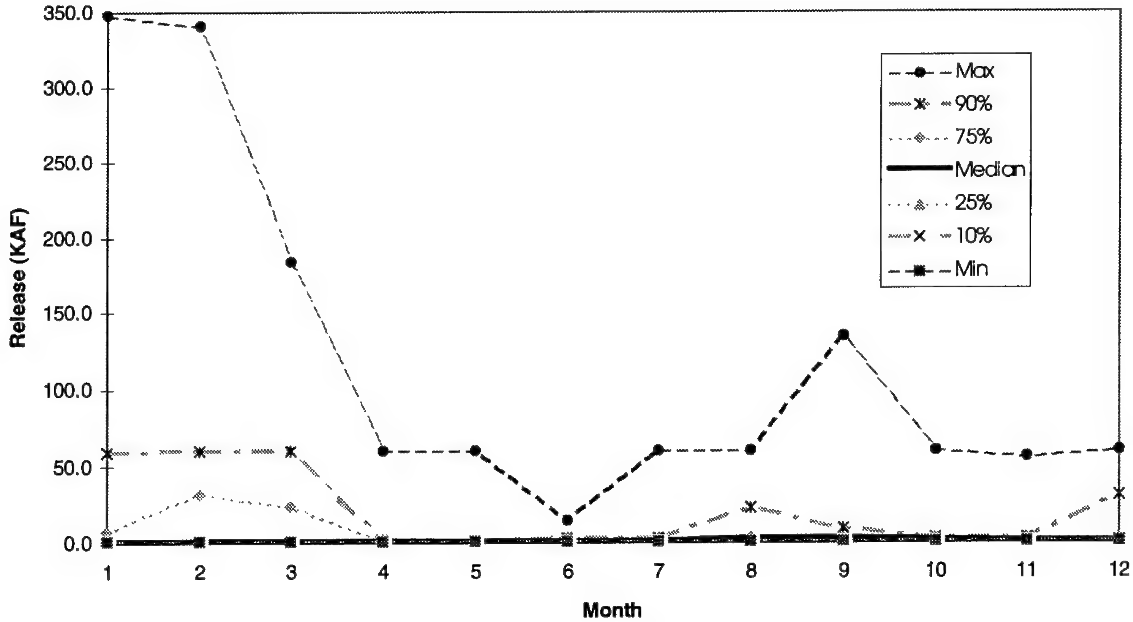

Figure 3.7 Percentile Plots for HEC-PRM Alamo Release Results for Composite Penalty

To verify this presumption, the HEC-PRM results were analyzed using time series analysis methods and scatter plots. Cross-correlation tests indicated that there is very little correlation between changes in release and changes in storage but there is significant correlation between changes in release and changes in inflow. Scatter plots also indicate that there is little correlation between release and storage but there is noticeable correlation between release and inflow. Figure 3.8 shows that it would be difficult to make a release decision based on storage, since such a wide range of flows occur at a given storage level. Figure 3.9, however, shows that there is a recognizable pattern and suggests that inflow would be a good indicator to use for making release decisions. Therefore, the first operating rule tested in the simulation model was designed to make release decisions based on a monthly target storage and current inflows. This rule form was tested first at a monthly time step to try and mimic the storage pattern from the HEC-PRM results.

Figure 3.10 shows how the storages resulting from the simulated operating rule compared to the HEC-PRM resultant storages. The major difference between the two is that HEC-PRM drafted the reservoir just before each major flood event to minimize large deviations from target. The simulation model does not draft the reservoir before a flood event, because decisions are made strictly on deviation from target and current inflow quantities. Nonetheless, the release rule was adjusted to approximate the magnitude of the peak storage quantities produced by HEC-PRM. After the monthly rule was deemed satisfactory, the rule was converted and refined for a daily time step.

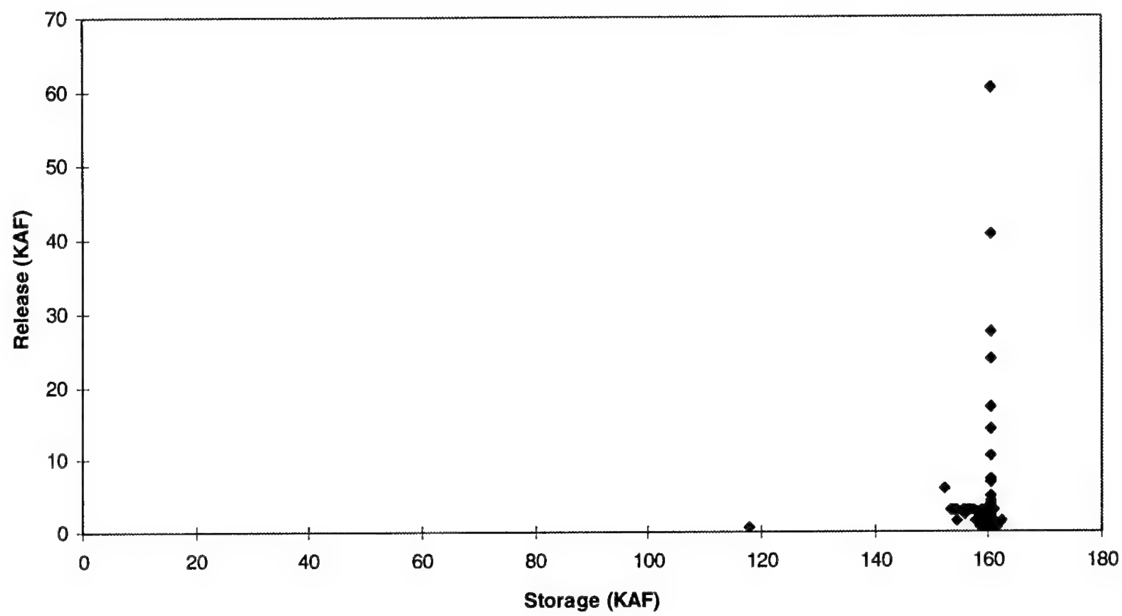

Figure 3.8 HEC-PRM Storage versus Release for July (1890 - 1993)

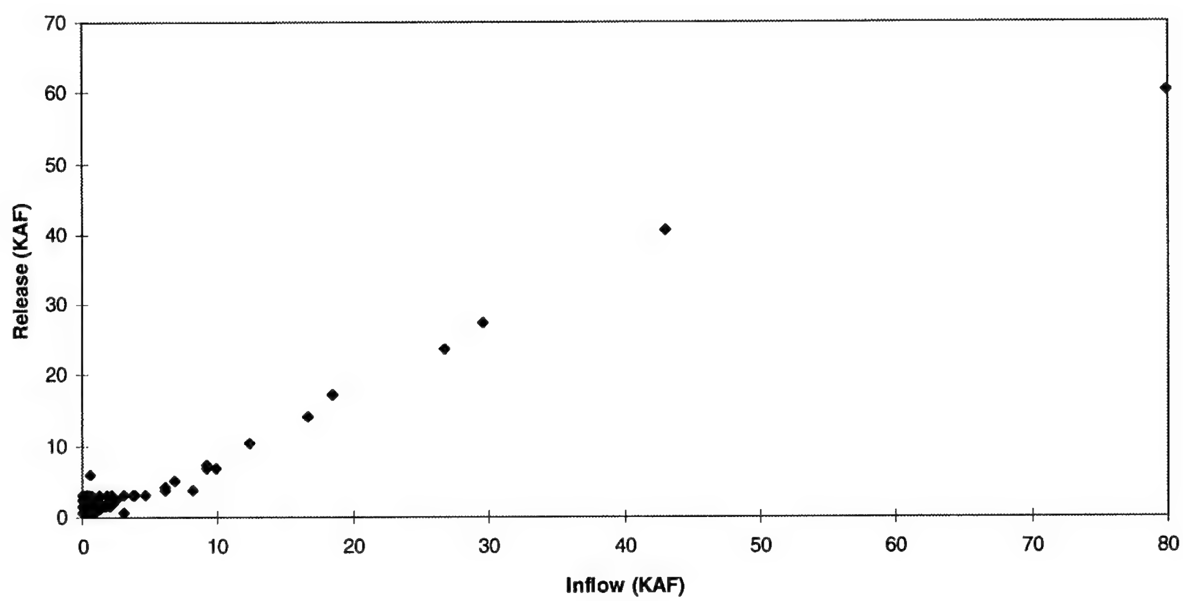

Figure 3.9 HEC-PRM Inflow versus Release for July (1890 - 1993)

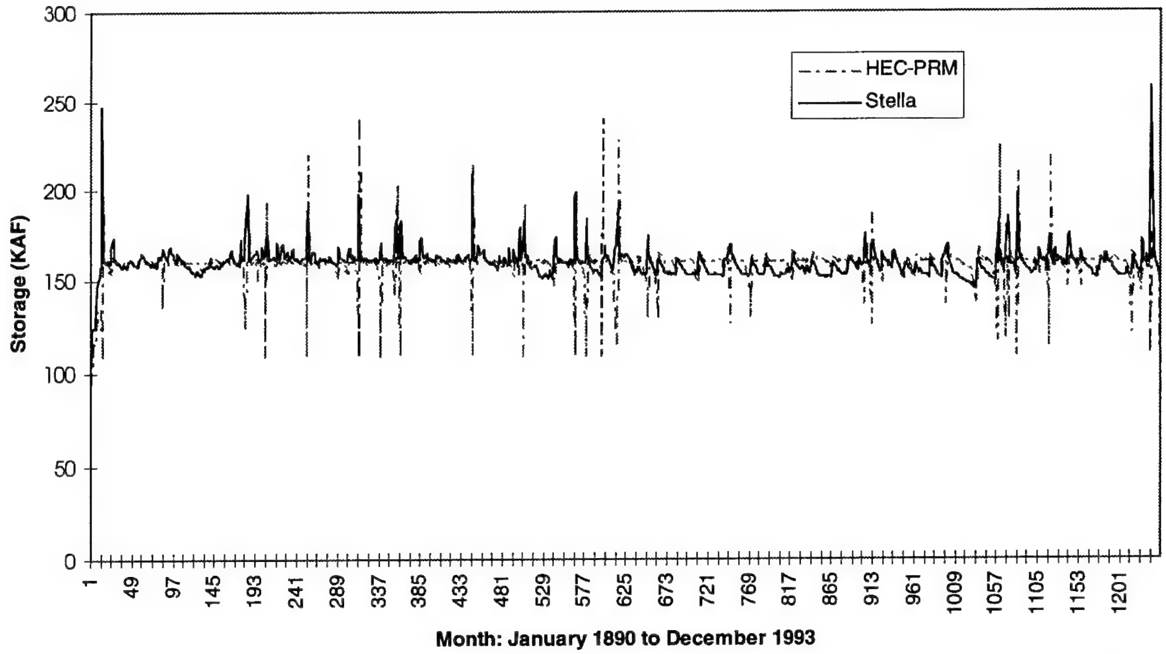

Figure 3.10 Comparison of Resultant Monthly Storage: Simulation and HEC-PRM

3.7 Offer Alternatives for Conflict Resolution

For most cases, the analyst would have results for several alternatives to present to the advocacy groups. The analyst could provide information in the graphical forms shown above, along with yield and reliability information. For this report, only one alternative was analyzed fully, and it is compared to the results of a previous study performed by the Los Angeles District U.S. Army Corps of Engineers using simulation alone.

3.8 Comparison of Results

As part of the conflict resolution efforts of the BWRCTC, the Los Angeles District U.S. Army Corps of Engineers performed a modeling study of Alamo Reservoir and the Bill Williams River using a simulation model (HEC-5). The report (BWRTC 1994) presents results for ten different main alternatives (two represent past and present operations) and four variations of the preferred main alternative. The alternatives were evaluated according to a series of yield and reliability criteria. Table 3.1 compares results for the operational criteria for the study done by the Los Angeles District U.S. Army Corps Office (labeled *Simulation*) and the combined modeling approach performed for this report (labeled *Combined*).

The *Compare* column in Table 3.1 indicates whether the operating rule formulated using the combined approach produced better or worse results than the operating rule formed using simulation alone (when tested over the historical record of daily inflows). Table 3.1 illustrates that the alternative generated using the combined modeling strategy produces results very similar to the alternative recommended by the BWRCTC. This similarity is noteworthy, since only one alternative was generated using the optimization model and then refined using simulation. The study done as part of the BWRCTC evaluated at least eight potential operating strategies. These results suggest that optimization models using the RUC Method can effectively screen alternatives to help focus more detailed simulation analysis.

Chapter 4

Conclusions

An analytical reevaluation of reservoir system operation can provide very useful information to help resolve conflict over water use. The proposed modeling strategy using an optimization model to screen alternatives and a simulation model to refine and test operational alternatives can be an effective way to discover innovative strategies to more closely meet conflicting demands. By using the optimization model to screen alternatives, the simulation modeling can be more focused and efficient. Although this modeling strategy does not address all aspects of conflict resolution activities, it can help groups start communicating through the identification of demands and quantification of objectives. This allows groups to discuss and address specific conflicts instead of vaguely perceived problems. Furthermore, the systematic procedure for developing and evaluating operational alternatives can help advocacy groups sort through the myriad of data necessary to understand reservoir system operation. Hopefully, the modeling results will provide a viable range of alternatives to allow the groups in conflict find a satisfactory operation plan to end the conflict.

One of the problems encountered when trying to apply this type of approach for reservoir systems is the difficulty in quantifying objectives for environmentally related uses. The Relative Unit Cost Method presented in this report helps mitigate this problem. The RUC Method allows the use of optimization models to analyze reservoir systems even when economically based penalties are not practical. Even if most water management objectives can be accurately represented using economic techniques, the RUC Method can still be used to quantify those objectives that cannot be suitably represented using economic techniques. The value functions produced from both methods can then be used in conjunction with one of the multi-objective programming techniques discussed in this report to generate promising alternatives.

The primary advantage of the RUC Method is its relative simplicity and ease of understanding. It allows a practitioner to construct water use value functions based on verbal descriptions of goals provided by interest groups. One possible disadvantage of the RUC Method is that the analyst must use broad statements of preference to build specific value functions. Also, since the method assigns magnitudes of unit costs for value regions instead of definitive penalty values for specific magnitudes of reservoir storage or release, the analyst must test the effectiveness of the penalty function by comparing optimization results to expected operational patterns based on the verbal water management objective. Subtle errors in the value functions may be difficult to discover through this testing method. The possibility of these errors coupled with the broad preference statements makes it possible that the optimization results do not accurately approximate the non-inferior set of solutions. However,

due to the complex nature of multipurpose, multiple reservoir systems, it is likely that even with these potential errors, the combined procedure may provide insight and creative solutions that would not be gained by simulation alone.

Appendix A

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Appendix B

Painless Penalties: A Penalty Function Generating Tool

One of the most laborious tasks required to apply HEC-PRM is the generation of numerical penalty functions for the water management objectives. The penalty functions must be formulated in a specific format and satisfy certain mathematical criteria. To facilitate these tasks, a penalty function generating tool was developed. The computer software tool is called *Painless Penalties*. The tool offers a graphical user interface running in Microsoft ® Excel, a Windows based spreadsheet. The program is menu driven, and data is entered through dialog boxes. A series of figures is presented to give a brief overview of the software.

Figure B-1 shows a typical screen and menu with a sub-menu open. Figure B-2 shows the dialog box that prompts the user for information to identify (name) the new penalty function. Figure B-3 shows the dialog box that allows the user to specify descriptive parameters of the penalty function. This dialog box allows the user to specify the breakpoints in various units (such as Storage or Elevation) and the program converts the input information to the format required by HEC-PRM. This conversion is available only if the user has supplied elevation, area, and capacity data for the reservoir. Figure B-4 shows how the specific penalty breakpoints and values or slopes are entered. Figure B-5 displays how the user can select multiple penalty functions to add together to form a composite function. Figure B-6 shows a sample of a penalty function plot, which the program provides for each new penalty function calculated.

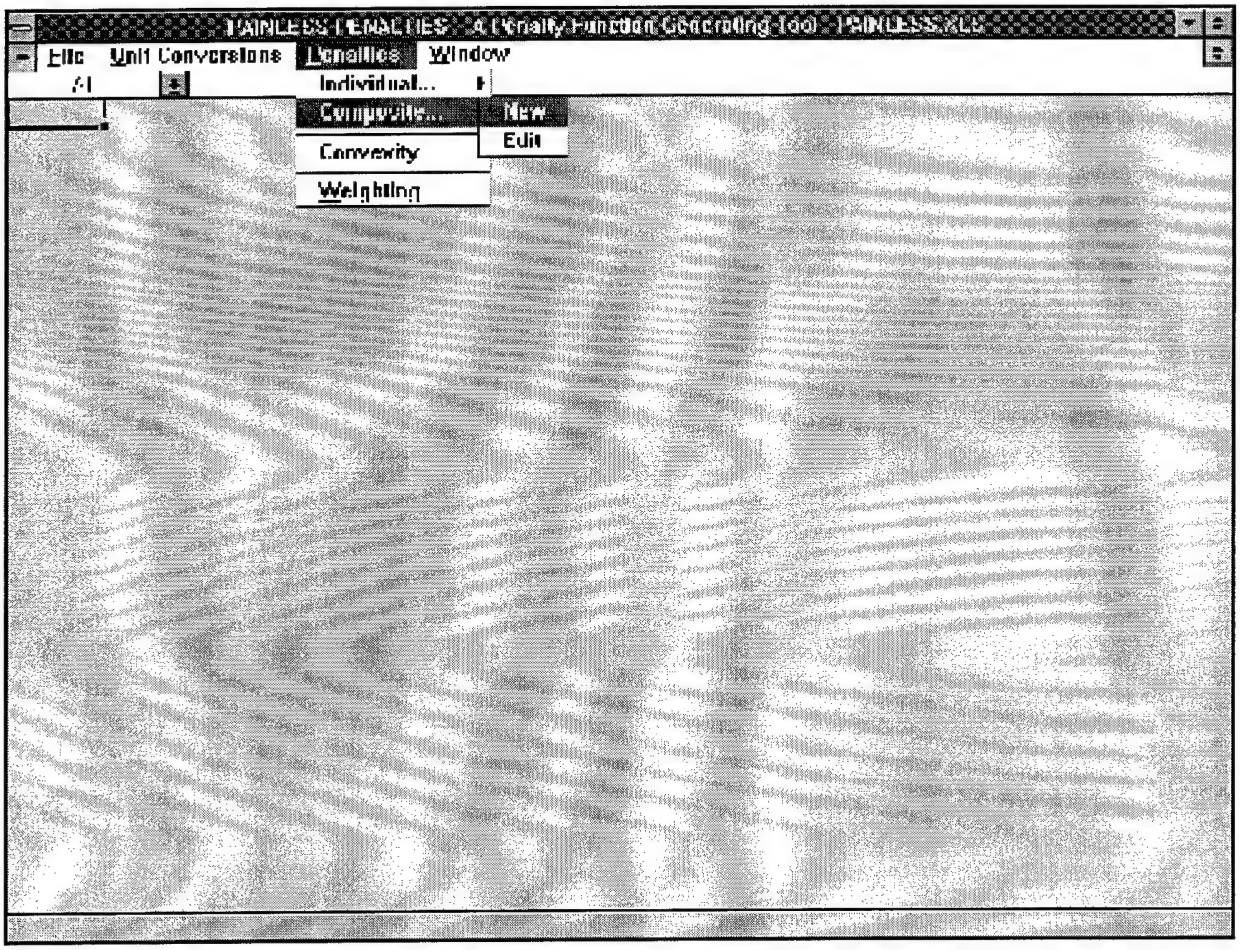

Figure B-1 Example of Painless Penalty Screen and Menu

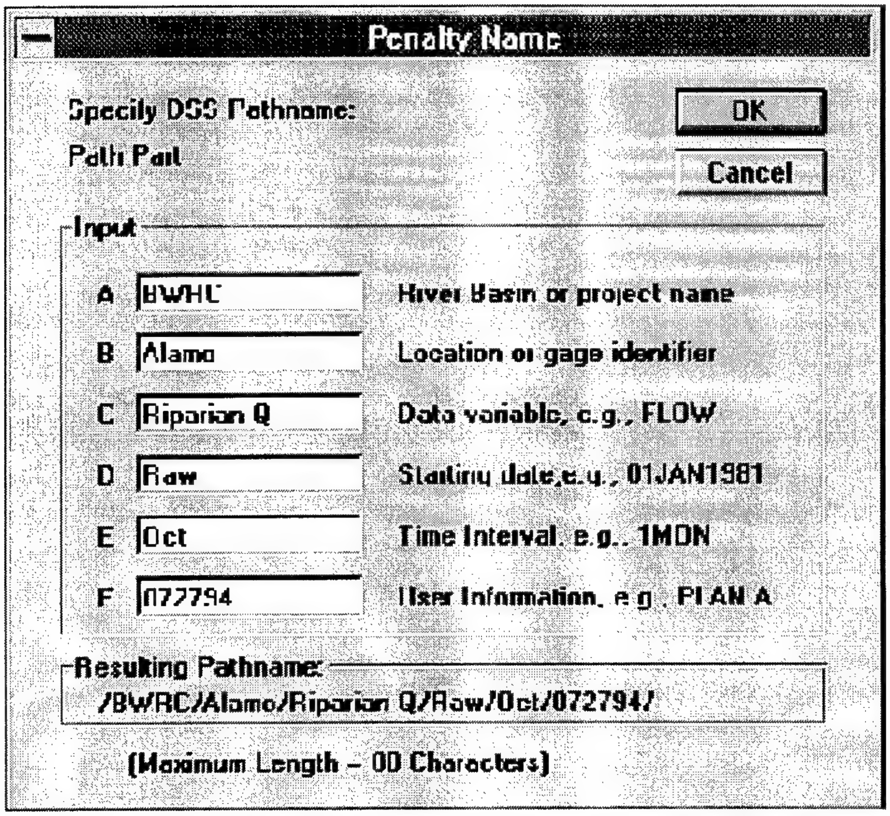

Figure B-2 Dialog Box to Specify Name for a New Penalty Function

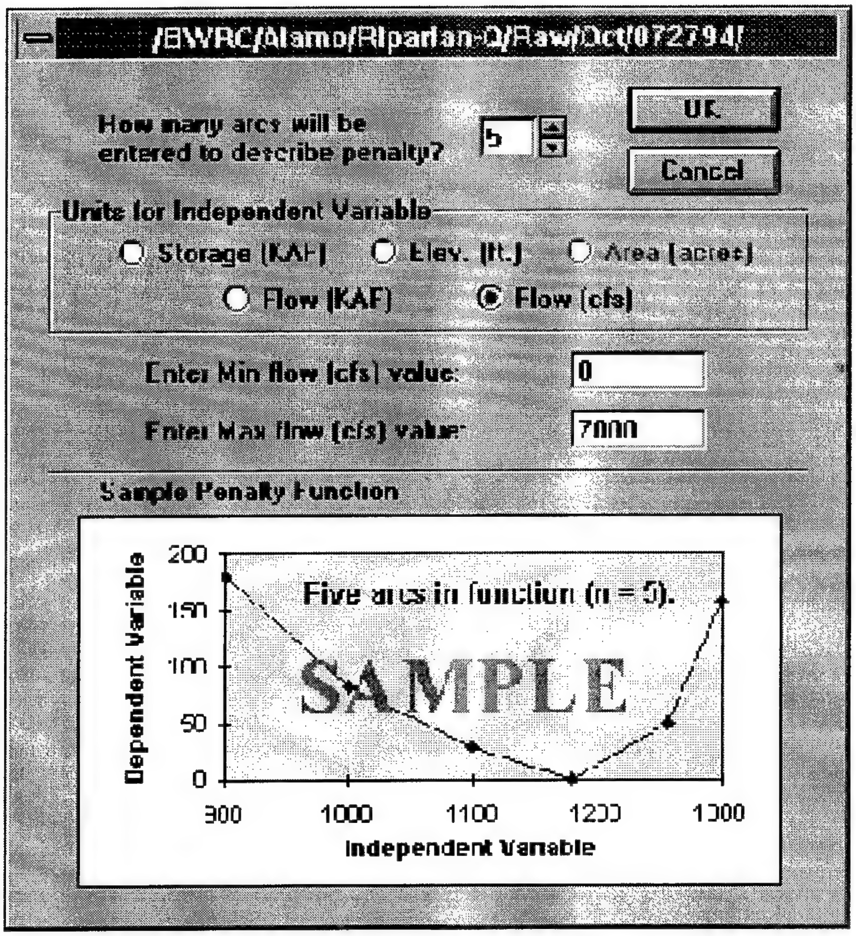

Figure B-3 Dialog Box to Specify Penalty Function Parameters

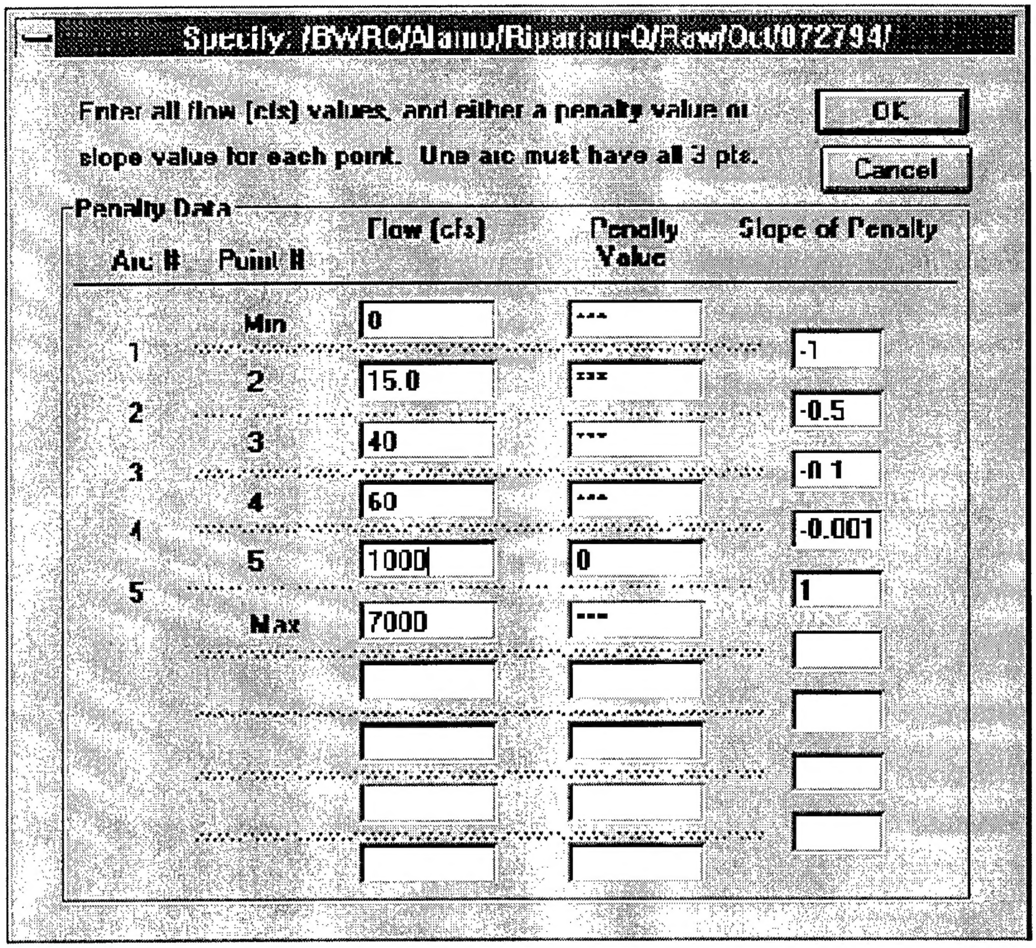

Figure B-4 Dialog Box to Specify Penalty Breakpoints and Values or Slopes

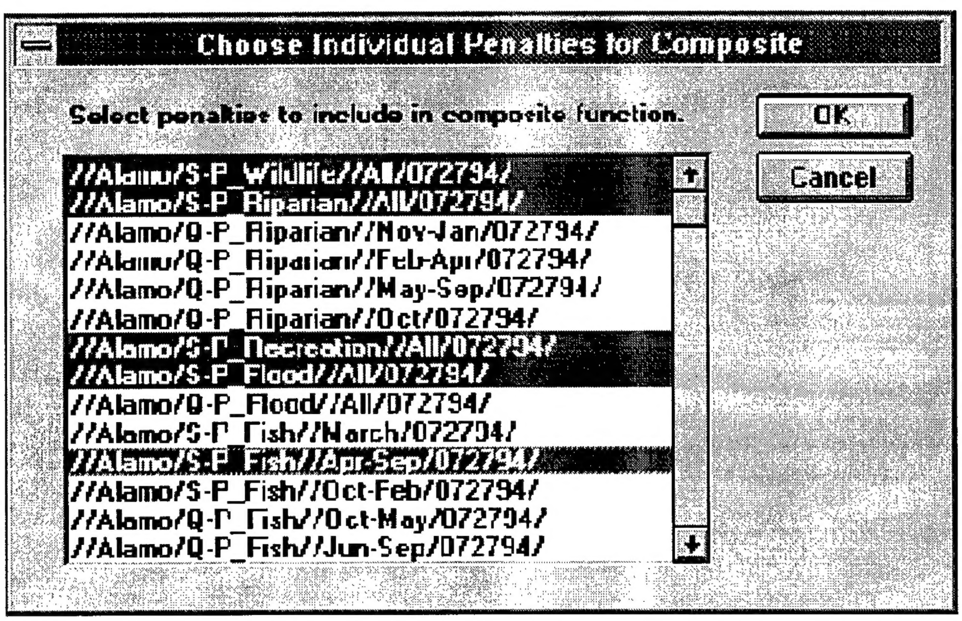

Figure B-5 Dialog Box to Select Individual Penalties to Composite

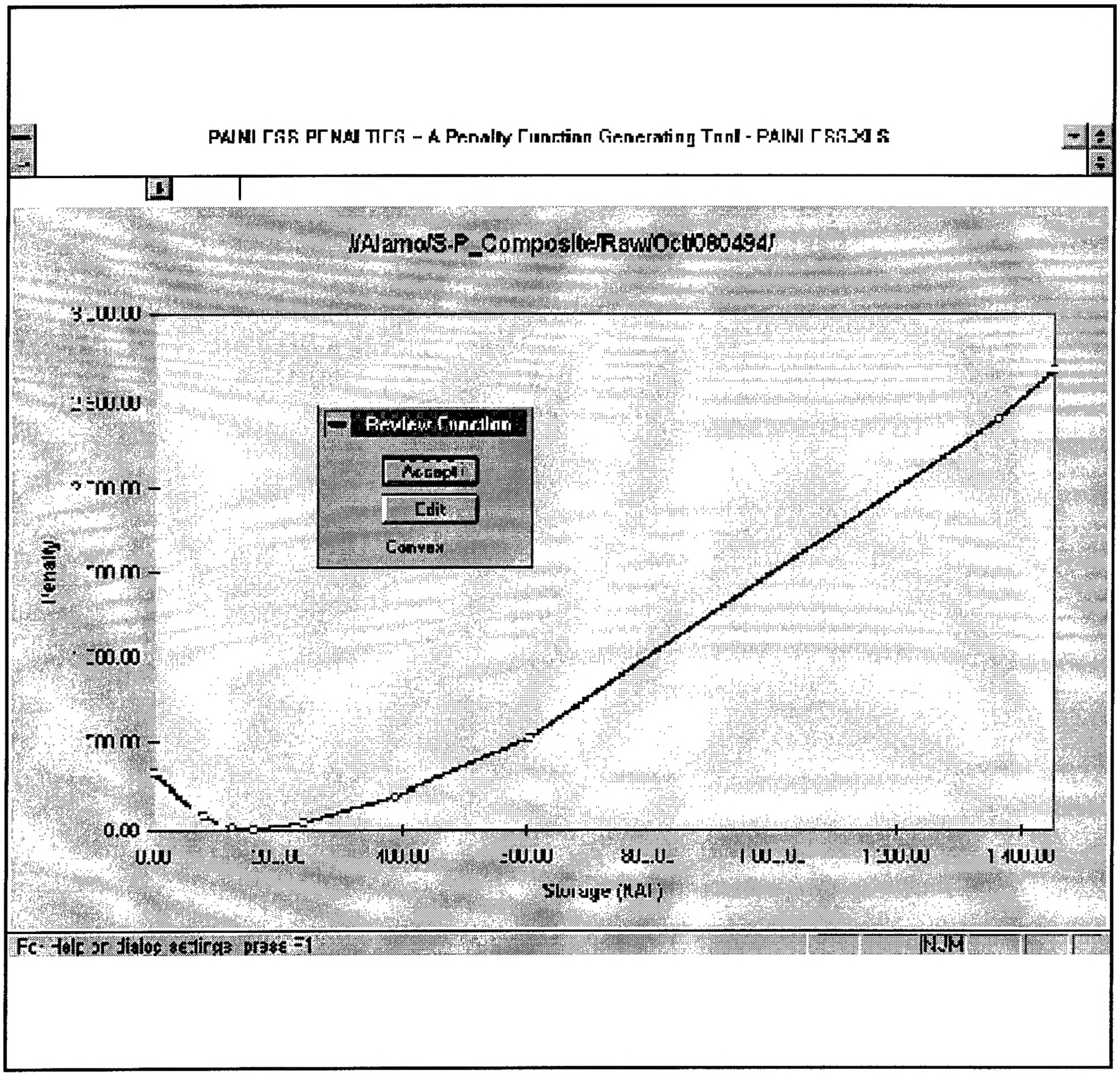

Figure B-6 Sample Plot of Newly Calculated Penalty Function in *Painless Penalties*

Appendix C

Penalty Functions Used for Case Study

This appendix provides the numerical data for the penalty functions for the Alamo study calculated using the RUC Method. The composite penalty functions are plotted in Figures C-1 through C-3. Figure C-1 illustrates the three different penalty functions for storage considering all objectives. The penalty function for October through February is very similar to the one for April through September. Figure C-2 shows that the release penalties do not very much for large releases, but Figure C-3 illustrates important seasonal differences between the release penalty functions at low releases (0 to 10 KAF/Month).

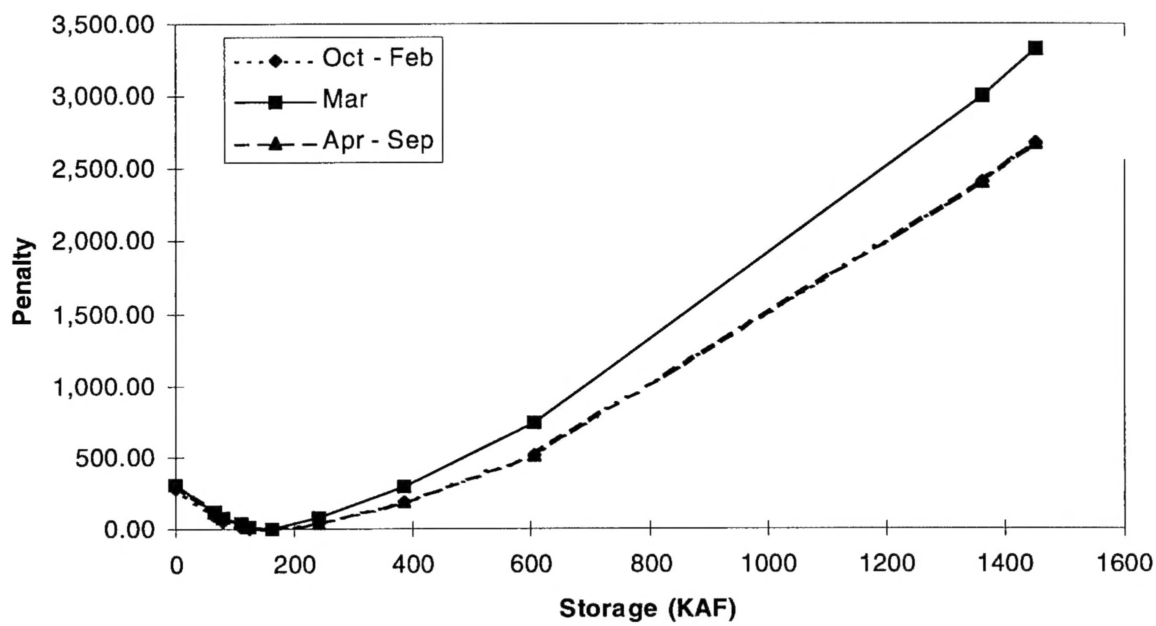

Figure C-1 Alamo Composite Storage Penalties

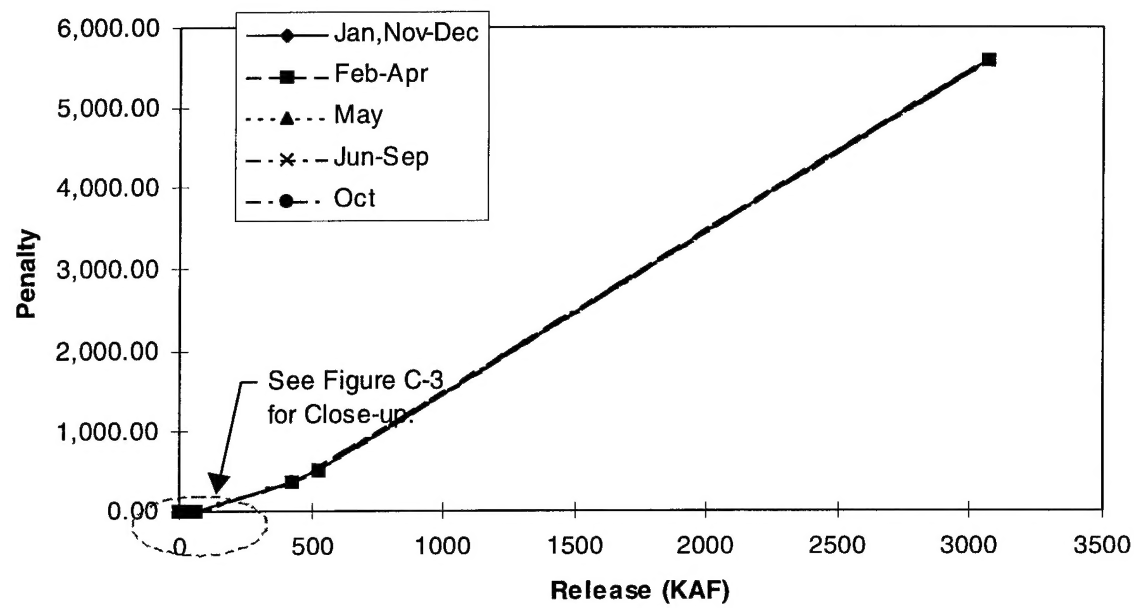

Figure C-2 Alamo Composite Release Penalties

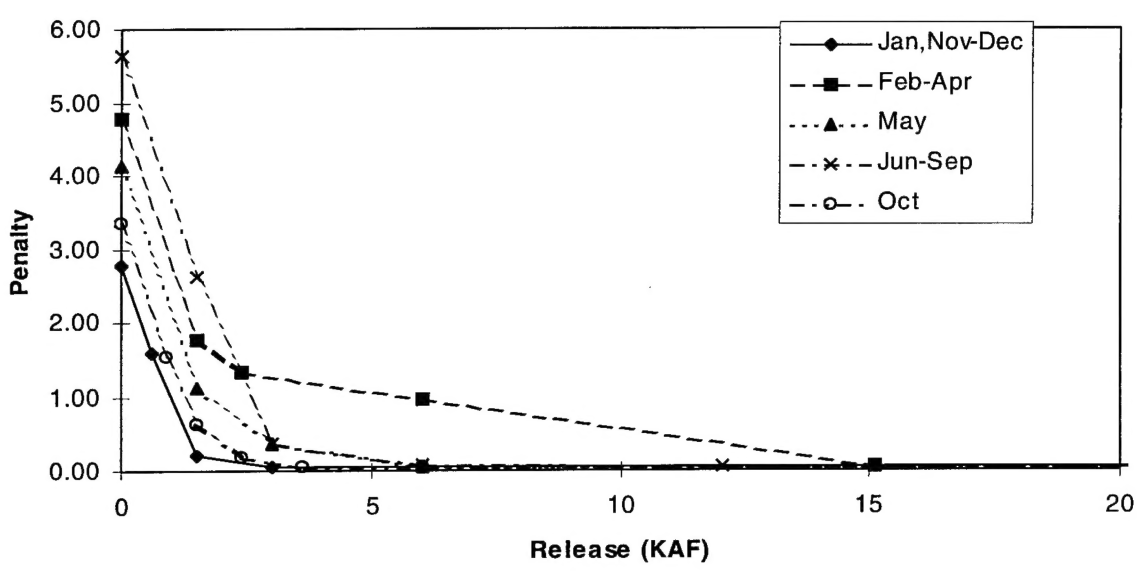

Figure C-3 Alamo Composite Release Penalties (Detailed View)